Economically Sustainable Development of Wave and Tidal Stream Energy Technologies

Andrew MacGillivray

Doctor of Philosophy

THE UNIVERSITY OF EDINBURGH

2016

"Man cannot discover new oceans unless he has the courage to lose sight of the shore."

Andre Gide.

"If something is important enough, even if the odds are against you, you should still do it."

Elon Musk.

"I made 5,127 prototypes of my vacuum before I got it right. There were 5,126 failures. But I learned from each one. That's how I came up with a solution. So I don't mind failure."

James Dyson.

Abstract

The wave and tidal energy sectors have received much interest in recent years, from policy-makers attentive to the prospect that ocean energy technologies could be capable of contributing towards meeting environmental targets; from utility companies that expressed interest in developing, constructing and operating array projects to export large quantities of clean energy from ocean based resources; and from Small to Medium Enterprises (SMEs) and large multi-national Original Equipment Manufacturers (OEMs) that were interested in undertaking technological development to commercialise wave and tidal energy converters that could successfully harness the energy contained within the ocean waves and tides.

Within the existing research, development and innovation environment that has largely dominated the development of wave and tidal energy to date – rapid development of large MW-scale devices capable of utility scale power generation – technology developers have failed to reach the level of deployed capacity that was initially anticipated, despite the significant level of investment that has taken place. Indeed, the expected contribution of ocean energy in the wider energy mix, which has been written into policy documentation at both national and European level, has so far failed to materialise in the form of prolific multiple device array deployments. The research, development and innovation environment has not delivered on its intended objective of demonstrating commercial technology readiness, and the historic development trajectories for ocean energy technologies may not represent the most cost-effective route to product commercialisation.

This research explores the wave and tidal energy research, development, and innovation environment through extensive stakeholder engagement within the ocean energy sector, and through application of suitable techniques from innovation theory.

The purpose of this research was three-fold. Firstly, an objective analysis of the development of the wave and tidal energy sectors – building a comprehensive understanding of their development to date through extensive stakeholder engagement, and comparing wave and tidal energy technology development with that of historic energy technologies that have successfully entered into commercial operation – was necessary in order to identify whether the attempt by ocean energy technologies for rapid up-scaling of technology is consistent with the develop-

ment pathway that was followed by energy technologies which have successfully transitioned from novel invention to full commercial operation. This work identified several dichotomies that are present in the nascent stages of technology development in the wave and tidal energy sectors.

Secondly, the uncertainties surrounding existing capital and revenue costs, and the uncertainties within the potential future cost reductions associated with current technology trajectories, could lead to unsustainable investment requirements. Commercialisation of wave and tidal energy technology is predicated upon significant cost reduction – the current technology costs are not feasible for large scale roll out of technology. A research focus on the economic uncertainty through application of learning theory and a learning investment sensitivity analysis was anticipated to demonstrate the economic impact of minor perturbations from idealised reference assumptions. The results from this work suggest that even minor perturbations in input parameters have substantial negative impact on overall investment requirements to bring technology to a level of cost competitiveness.

Thirdly, the policy landscape surrounding wave and tidal energy development has not been specifically compared and contrasted, using a number of performance metrics, to a technology which was subject to similar expectations in the form of income streams – wind energy technology. The causes and motivations for the rapid transition to large-scale technologies and 'accelerated innovation' within ocean energy technology were considered within this research, which suggested that a mismatch between policy support and technological readiness could misguide and misdirect the innovation pathway, harming the commercialisation prospects of ocean energy technology.

In order for the successful emergence of economically sustainable wave and tidal energy technologies, a paradigm shift may be necessary, a change from the current approach that has to date dominated technological development within both the wave and tidal energy sectors.

This research draws together industry consultation with academic insight to identify an optimised innovation pathway, culminating in a policy appraisal to guide and inform economically sustainable development of wave and tidal energy technologies.

Lay Summary

This thesis proposes that the current wave and tidal energy research, development and innovation environment is not conducive to enabling economically sustainable development of wave and tidal stream energy technologies.

This thesis presents the importance of a formative phase of technology development – a phase characterised by multiple unit iterations, generally at small-scale when compared to the final commercial product, with a relatively short time-span between subsequent unit deployments, prior to the emergence of a commercially successful technology. Wave and tidal stream energy technology developers are attempting to bypass this formative phase, targeting commercial operation within the first units, with most focused on large-scale technologies.

Cost reduction, an essential requirement for sustained deployment of ocean energy technology, is often represented in industry reports by optimistic scenarios that enhance the attractiveness of the technology. This thesis demonstrates that even minor changes to scenarios, making them more reflective of wider technology norms, can result in substantially increased investment requirements. In a comparison between large and small-scale technology, it is proposed that small-scale technology development and deployment would offer a more economically attractive and sustainable means of progressing through a formative phase of technology development.

An investigation in the use of policy support mechanisms has considered the shift between technology development support and market development support. The wave and tidal energy sectors have experienced transition to market dominated support mechanisms before a market-ready technology was available. This thesis suggests that ocean energy policy support is misaligned with the requirements of technological development.

The conclusions present recommendations that could alter the structure of technology development support, promoting a more economically sustainable formative phase of technology development, and establishing greater levels of confidence in novel energy technology.

Acknowledgements

There are many people to whom I owe much thanks, for which I am extremely grateful. This journey has been a challenge, but one in which I have been privileged to undertake.

Firstly, to supervisors past and present: Prof. Ian Bryden, Prof. Ignazio Viola, Prof. Robin Wallace, and Henry Jeffrey. Each has provided insight and oversight; critique and encouragement – this project would not have been possible without them, and I am extremely thankful for the contribution made by each in shaping this project. I would particularly like to thank Prof. Robin Wallace and Henry Jeffrey for their valuable input, and commitment to supporting this work.

Special thanks go to Henry Jeffrey, not only for his wise counsel, mentoring and guidance, but also for his friendship. Much of the work I have been able to participate in comes as a direct result of his extensive network of contacts, and willingness to provide opportunities.

Friends and colleagues at IES, whether through work or through social activities, it has been a pleasure to work alongside and get to know so many excellent people. Office mates past and present have provided delight, and at times irritation, but more often than not a refreshing break from the screen when it was necessary. Thank you!

The Policy and Innovation Group, of course, are due a special mention for all the graft, the sweat, the tears, but all round most excellent teamwork. I have enjoyed being part of the PIGs (you know who you are), you have been fantastic, and I'll miss the team talks.

The International Network on Offshore Renewable Energy, who have organised a number of excellent Symposia events and engaged a large number of influential researchers, has been pivotal in opening many doors for me, for colleagues in Edinburgh, and friends further afield. I am pleased to have been able to participate, and get to know so many wonderful researchers in offshore renewable energy. These guys and girls represent the future of our industry! It has been a pleasure to meet so many talented and gifted engineers, mathematicians, scientists, socio-economic analysts, environmental experts – and more – and to be able to call them friends. In particular, Adrian de Andres, who has been a colleague and a close friend since our posters were first placed next to each other – thank you for all your contribution during your time here in Edinburgh.

Funding was most gratefully received for this research. To Fundación Iberdrola, thank you for giving me the opportunity to be one of your scholars. It has been a true privilege to have had your support for this work. Thanks also go to The University of Edinburgh and the Energy Technology Partnership who provided the additional funding that enabled this research to take place.

Special thanks to my family, for their unending support, kindness and generosity. Hopefully I haven't bored you with too many conversations about my work...

Finally, to Emma and Joshua – thank you for being patient with me! It's been a long time coming, but I hope that the hard work and effort has paid off. Without your love and support I wouldn't be where I am today, and this is dedicated to you. I couldn't have done it alone.

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

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Nomenclature

Definition	**Description**
5PL	5 Parameter Logistic function
ADEME	French Environment & Energy Management Agency
CAPEX	CAPital EXpenditure
CDF	Cumulative Distribution Function
CFD	Computational Fluid Dynamics
CSCR	Capacity before Sustained Cost Reduction
DECC	Department of Energy & Climate Change
EAP	Electro-Active Polymer
EMEC	European Marine Energy Centre
EMR	Electricity Market Reform
GHG	Green House Gas
FEA	Finite Element Analysis
GW	Gigawatt
GWh	Gigawatt-hour
IEA	International Energy Agency
IP	Intellectual Property
kW	Kilowatt
kWh	Kilowatt-hour
LI	Learning Investment [£]
MEAD	Marine Energy Array Demonstrator (DECC funding)
MRCF	Marine Renewables Commercialisation Fund
MRPF	Marine Renewables Proving Fund
MW	Megawatt
MWh	Megawatt-hour
NER300	New Entrants Reserve 300 (EU technology demonstration funding)
NREAP	National Renewable Energy Action Plan

OECD	Organisation for Economic Cooperation and Development	
OEM	Original Equipment Manufacturer	
OES	Ocean Energy Systems Implementing Agreement	
OPEX	OPerational EXpenditure	
OTEC	Ocean Thermal Energy Conversion	
OWC	Oscillating Water Column	
OWSC	Oscillating Wave Surge Converter	
PDF	Probability Density Function	
PTO	Power Take-Off	
PV	Photovoltaic (Solar)	
Q-Q	Quantile-Quantile Plot	
R&D	Research and Development	
RD&D	Research, Design, and Development	
ROC	Renewable Obligation Certificate	
SC	Starting Cost	[£/kW]
SF	Scaling Factor	
SSE	Error Sum of Squares	
SI Ocean	Strategic Initiative for Ocean Energy	
SME	Small to Medium Enterprise	
TEC	Tidal Energy Converter	
TP Ocean	Technology & Innovation Platform for Ocean Energy	
TPL	Technology Performance Level	
TRL	Technology Readiness Level	
TW	Terawatt	
TWh	Terawatt-hour	
WEC	Wave Energy Converter	

Latin Symbols

α	Shape parameter (for Gamma distribution)
β	Scale parameter (for Gamma distribution)
b	Hill-slope of 5PL function
B	Minimum asymptote in 5PL function
H_s	Significant Wave Height [m]

s	Asymmetric coefficient in 5PL function
T	Maximum asymptote in 5PL function
T_p	Wave Peak Period [s]
T_e	Wave Energy Period [s]
x_f	x-coordinate of point at which "B + (0.9*(T-B))" is reached in 5PL function
x_i	x-coordinate of point at which "B + (0.1*(T-B))" is reached in 5PL function
x_{mid}	x-coordinate of point of inflection in 5PL function

Chapter 1

Introduction

1.1 Chapter Introduction

This chapter forms the foundation of this thesis, describing the problem statement that set the needs and requirements of this work, and outlines the approach that was taken to identify and address the specific research questions. An overview of the thesis is presented, providing clarity on the structure and approach that this document will follow.

It should be made clear that this research is about ocean energy technology (specifically wave and tidal energy), the readiness of such technology for commercial application, and the confidence of investors and financiers in supporting continued technology demonstration, development and deployment. The work is rooted in engineering, and other aspects explored within this thesis will be biased towards those areas that impact the strategic direction of technology development and innovation.

An important clarification must be noted – the tidal energy technology considered within the context of this thesis considers only tidal current and tidal stream technologies, technologies that utilise the horizontal motion of water to produce electrical power in either unidirectional or multi-directional flows. Tidal range technologies, which utilise the vertical rise and fall of the tides to drive low head hydro-electric turbines, are not discussed further within this research.

1.2 Problem Statement

The wave and tidal energy sectors appear to be making efforts to progress to multi-MW array level deployment – the installation and operation of several utility-scale devices in one location – in order to confirm and demonstrate that the technology is attractive for wider use in the energy sector (RenewableUK, 2013; Carbon Trust, 2011). Indeed, the perceived customers for wave and tidal energy technologies were utility companies, whose interest lies in multi-MW scale deployment and large scale power generation. However, the slower-than-anticipated progress in the deployment of these early arrays has confirmed that there are still concerns as to the economic viability of such projects, particularly within project developers and investors (MacGillivray *et al.*, 2013a). Given the substantial investment requirements, very few are willing to take the initial financial risks in order to help secure the deployment of these early arrays (Badcock-Broe *et al.*, 2014). Despite the drive to produce technology that is suited for utility customers, utility companies are uninterested in the slow pace of technology development and are reducing their level of investment within the sector (Nichols, 2013).

The requirement for both capital grant support and revenue support schemes (such as feed-in tariffs) to enhance the 'bankability' of wave and tidal energy converters is characteristic of all early stage technology demonstration (Grubler *et al.*, 2014). While it is likely that technology costs will decrease in the long term, the slow progress in deployment, despite attractive incentive mechanisms in place in a number of countries across the globe, raises questions as to whether wave and tidal energy technology is indeed ready to make the progression from technology development and demonstration on to deployment of a pre-commercial array.

Wave energy has received attention (albeit at fluctuating levels of intensity) since the 1970's (Drew *et al.*, 2009; Cruz, 2008), however modern development of both the wave and tidal energy sectors has taken place with greater focus on developing commercial technologies since the mid 1990's. Two decades of increased political interest in wave and tidal energy has been experienced, yet technological development has failed to reach the expectations of technology developers, politicians and utility companies (Magagna and Uihlein, 2015); many of the technologies under investigation are still struggling to demonstrate long-term, reliable, autonomous operation (Vantoch-Wood, 2012c).

More recently, tidal energy technologies have achieved greater levels of demonstrable power generation than wave energy technologies, and are generally regarded by ocean energy stakeholders as closer to commercialisation (MacGillivray *et al.*, 2013a). The distinction between wave and tidal energy technology, and the difference in the level of technology development is here noted; the two sectors are at different levels of technology readiness – the development of wave energy technology lags behind that of tidal energy technology.

However, within both wave and tidal energy sectors, perceived 'leading' technology developers are struggling to reach financial close of early array demonstration projects, with some of the leading technology companies entering administration, significantly down-sizing, or divesting from marine energy altogether. High levels of uncertainty still remain across several aspects of ocean energy sector commercialisation – uncertainties that span technical, economic, and political circles (Magagna and Uihlein, 2015; MacGillivray *et al.*, 2013a). A critical juncture has been reached: Is there justified confidence in the technology for progression from device development to deployment of arrays, or is a change in research, development and innovation environment needed in order to facilitate the emergence of a truly commercial and economically sustainable ocean energy sector?

Before outlining the research questions, a hypothesis will first be presented:

The dominant research, development and innovation environment being pursued within wave and tidal energy in the UK – rapid progression to MW-scale technology and development of multi-MW arrays – is not conducive to developing economically sustainable and reliable technology, nor facilitating the emergence of commercially viable wave and tidal energy technologies, in a timely and affordable manner.

1.3 The Research Questions

In order to test the research hypothesis, a number of research questions were set. These research questions were confirmed by early research, the results of which are considered in greater detail within the following chapters of this thesis.

Firstly:

Can wave and tidal stream energy technology readiness and attractiveness be evaluated using 'Diffusion of Innovation' and 'Learning' techniques from innovation theory to provide insight into the effectiveness, appropriateness and affordability of the current research, development and innovation environment?

The wave and tidal energy sectors have seen over £120 million in public funding since the year 2000 to stimulate innovation (Research Councils UK, 2014), however, fundamental development and operational challenges still remain to be addressed. The existing innovation pathways for a number of wave and tidal energy technologies have perhaps overlooked intermediate development steps, and there may exist opportunity to learn from historic technology innovation and development in order to influence how structured ocean energy technology development and deployment can take place from this point forward.

As a subset of the above question, the following questions are raised:

- *What is the role of unit iteration and unit deployment in the overall innovation pathway for technological development?*
- *What is the role of unit scale within the early stages of technology development and innovation?*
- *What are the plausible overall learning investment requirements in commercialising development of wave and tidal energy technologies within the present research, development, and innovation environment, and is this an affordable development trajectory?*

Historic evidence from the development pathway of energy sector technologies would perhaps shed light on suitable innovation pathways for ocean energy, and may suggest a pathway very different to that being pursued by the wave and tidal energy sectors. No energy sector technology has become an overnight success, but investigation of the number of unit iterations may provide some insight into plausible needs and requirements within the development of ocean energy technologies, particularly with regards to the number of unit deployments before successful large-scale adoption of technology and unit and industry-level up-scaling could be anticipated to take place.

It is noted that energy technologies, over time, experience significant operational cost reductions through economies of scale (Aanesen *et al.*, 2012; Grubler *et al.*, 2014; Junginger *et al.*, 2010a). In particular, it is more economically beneficial to maintain a smaller number of large capacity units than to maintain a large number of small capacity units. This is fully evident in the wind energy sector, technology analogous to that of wave and tidal energy converters, which started small but did not stay small. The basis of this research, however, is that the starting point of the wave and tidal energy sectors may benefit from a ‘starting small’ approach, although it is fully acknowledged that once a successful development and demonstration of technology, across a number of unit iterations, has taken place, wave and tidal energy technologies too could progress in a similar manner to that of wind energy.

Given the uncertainties and unknowns that still linger over the nascent technology within the wave and tidal energy sector, the current development and deployment trajectory using MW-scale technology may not be affordable, given a range of plausible variations in specific parameters associated with ocean energy technology deployment. The implications of the uncertainty, in terms of overall learning investment, require comprehensive investigation in order to enhance understanding. The effect of deviation from optimistic input parameters could have a dramatic impact on the economic feasibility of cost reduction and deployment, a fact which is largely disregarded in many industry based reports. The impact of scale on learning investment over a number of iterations has not been explicitly discussed, and there is opportunity for this research to investigate this further.

One point of caution that should be outlined at this stage is the different opportunities to scaling that exist within wave and tidal energy technologies. Different scaling laws apply to tidal energy converters than to wave energy converters. The power output of tidal energy converters scales to the power of 2 with respect to the scaling factor (SF), due to the relationship between power output and swept area of the rotor (i.e. SF^2); for wave energy converters the power output scales to the power of 3.5 with respect to the scaling factor (i.e. $SF^{3.5}$) (Holmes, 2009). This is discussed further in Section 4.5.

Secondly:

How have the policies and funding mechanisms in ocean energy stimulated the research, development, and innovation environment within wave and tidal energy to date, and have the correct metrics been used in aligning appropriate policy with the developmental needs of the ocean energy sector?

Existing policy and support mechanisms within the wave and tidal energy sector have not overseen the diffusion of ocean energy technologies into the wider energy mix or security in the market for ocean energy, despite these being principal aims. The financial requirements for the progression from solo device demonstrations on to array deployments involves substantial economic risk to technology developers, project developers, and investors. The first commercial scale array project in the UK has been financed largely by public sector intervention (MeyGen, 2015) – an intervention that is unlikely to feature to the same extent within any future array project. However, the long-term success of the sector will rely on apposite policy support to ensure progression through the formative stages of technology development. Successful technology development will be required in order to re-establish support from private sector shareholders, investors and financiers. Appropriate policy mechanisms will be needed in order to bridge the gap between the current state of technological development and the point at which private sector investment can confidently re-enter. In particular, issues that could drive policy reform and improved sectoral development within ocean energy will be discussed. These include the lack of transparency in provision of operational and performance data across the ocean energy sector (Magagna *et al.*, 2014), and the need to balance sensitivities associated with intellectual property with the benefits of transparency and the sharing of data.

Thirdly:

Should support mechanisms for wave and tidal energy technology concentrate on technology development or technology deployment?

As a result of investigative work in previous research questions, the recommended focus of future wave and tidal stream energy technology innovation support can be identified: technology development (iteration and optimisation of technology) or technology deployment (array level construction and large-scale roll-out). These two alternatives represent very different trajectories, and the opportunities and limitations offered through each approach are not at present well defined, and offer room for further investigation.

The key aim and goal of this process will be to investigate and identify policy mechanisms and transitions from the experience of a more mature technology, in this case, onshore wind, and compare this to the policy landscape for the emerging wave and tidal energy sectors. Prudent observations may allow for apposite policy recommendations for the wave and tidal energy sector. By investigating the implementation of transition from technology-push to demand-pull orientated policy support mechanisms, it is envisaged that a more mature understanding of the symbiosis of ocean energy policy and technology development can be established.

Economically sustainable wave and tidal energy industries need robust policy measures in order to secure the future of the sector. If the wrong policies have been established at the wrong time, then this will not enable each sector to establish the fundamental building blocks needed in order to successfully navigate through the formative phases of technology development (Badcock-Broe *et al.*, 2014). During the early stages of technology development and demonstration a focus on return on investment and economic profitability is premature. Policy analysis will subject the existing mechanisms to scrutiny, and identify whether there are opportunities for the adoption of new policy approaches that would better facilitate the emergence of successful wave and tidal energy technologies.

1.4 A Brief Overview of the Research

The purpose of this research, and the justification as to why it is necessary, comes from a need to clarify and understand the impact that a drive for 'accelerated innovation' makes upon the research, development and innovation environment within the field of ocean energy technologies. In particular, there exists debate surrounding appropriate technology scales within the development of wave and tidal energy technologies – which, if remaining unanswered, could dilute the useful funding allocation provided to wave and tidal energy. Identifying the uncertainties, and highlighting the timing and importance of correct policy implementations is critical for the formation of a sustainable ocean energy future.

Utilising a combination of cross-transferable approaches derived from relevant practices in Innovation Theory, together with industry engagement through stakeholder interviews and workshops, this research aims to clarify the development of the ocean energy sector, assessing *measurable* progress in technology development and deployment within the wave and tidal energy sectors – culminating with a policy appraisal to guide technology development towards the goal of achieving economically sustainable and commercially viable formative phase development of wave and tidal energy sectors.

This research took a twin-track approach to its investigation – utilising insights from both industry and academic science – in order to ensure that the outcomes have a strong industrial grounding and application. It should be noted that this research has been carried out from a sector progression perspective, including the needs and requirements of technology developers, policy makers, and research funders. This thesis is written from the perspective of a neutral party that recognises the challenges that face each category of stakeholder. This thesis is a document that will be capable of informing technology developers and policy makers, in order to facilitate the transition towards an appropriate research, development and innovation environment. It aims to inform the means by which commercialisation of wave and tidal energy technologies can take place in a more economically sustainable manner, allowing technology to be de-risked, and providing confidence to private sector financiers and investors.

1.5 Methodology

Now that the research questions have been established, it is important to outline the methodology that will be followed in order to test the hypothesis and answer the research questions that have been set.

From an engineering perspective, the primary interest is in the direct development and enhancement of technology performance, however there is a direct influence of both economic and policy mechanisms that can strongly influence the pathway and direction of this technical development – and the success of the research, development and innovation environment as a whole. For example, inappropriate guidance or interference from profit driven or politically motivated sources could lead to sub-optimal technological development steps or inappropriately picking winners. It is through this understanding that this body of research focuses only on the core 'polical', 'economic', and 'technological' themes shown in Figure 1.1.

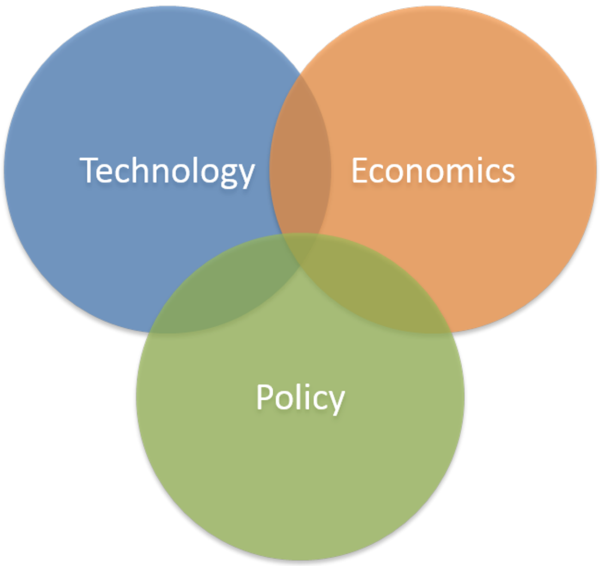

Figure 1.1: The three principal focus areas within this thesis

Research carried out for this thesis included ocean energy stakeholder engagement, which outlined some fundamental questions that still remain unresolved within the development of wave and tidal energy technology (MacGillivray *et al.*, 2013a). Early research also outlined some gaps in existing knowledge and identified where innovation theory and its application to the development of wave and tidal energy technology can enhance current knowledge. This industry based insight was utilised in conjunction with a literature review into innovation theory. This literature review identified suitable tools and techniques that would help provide substantiated evidence to support the research hypothesis and answer the research questions.

Two potential techniques from innovation theory were identified as being capable of providing enhanced understanding within the themes of technology and economics. These techniques are based in diffusion of innovation theory and learning theory. Consolidating these approaches with an analysis of the policy landscape supporting deployment of ocean energy technologies in the UK allows the threefold topics identified in Figure 1.1 to be addressed. The main body of analysis within this thesis takes place within chapters 4, 5, and 6, with a chapter for each of the main 'technology', 'economic', and 'policy' topics.

The thesis structure outlined below presents how analysis is carried out within each of the chapters, and the role that each chapter has to play in the wider context of this thesis.

1.6 Thesis Structure

The broad outline of the thesis is structured according to Figure 1.2, and is discussed below.

- The starting point for this body of work involved gaining an understanding of the state-of-the-art in wave and tidal energy technology development – a **technology and sector review**. This review broadly outlines the status of each sector, considering the technologies under development, challenges faced, and the perceived next steps for each industry.
- **Ocean energy stakeholder engagement**, consisting of interviews with technology developers, utility companies, supply chain companies and consultancies, follows – identifying gaps in knowledge and barriers to deployment within the ocean energy sector. Evidence is reported based on the analysis of the outputs of the stakeholder engagement process.
- Following on from the technology and sector review, a **literature review** investigating innovation theory is presented. This provides an introduction to innovation, and identifies the tools and processes from innovation theory that are utilised within the main body of the thesis to answer the research questions and validate the research hypothesis.
- **Innovation theory and practice** – explaining how the theory identified in the literature review is applied in practise within the main body of work – then presents the specific tools from innovation theory and the methodologies utilised in order to answer the research questions.

- **Application of the identified tools and processes** is presented within three chapters that consider the themes of Technology Trajectory, Learning & Economic Risk, and Policy.
- Analysis of the diffusion of innovations in energy technologies provides an overview of the formative phase of technology development, investigates trends associated with the wider energy sector, and identifies the specific stages of development that have been seen historically. Finally, these findings are compared to the development pathway being pursued by ocean energy technologies.
- Economic analysis and application of learning theory then introduces a learning investment sensitivity analysis, investigating the impact of minor perturbations on input variables on the theoretical learning and overall investment requirements for bringing ocean energy technology to a level of commercial competitiveness with offshore wind.
- An analysis of policy support for ocean energy technologies in the UK and wind energy technology in Denmark is then presented – assessing in particular the successes, failures, and limitations of ocean energy policy within the UK in comparison to the policies that shaped the emergence of wind energy technology in Denmark.
- Application of the identified analysis techniques (from innovation theory) and analysis of the results evidenced **misalignment** in the ability of the current ocean energy research, development and innovation environment to deliver on intended goals in an affordable and timely manner. Discussion of findings from each of the 'technology', 'economic', and 'policy' sections of this thesis, and the identification of misalignment between aspirations and the reality of ocean energy technology development, provides evidence for the requirements of a new policy recommendations to enable economically sustainable development of wave and tidal energy technologies.
- The conclusion of this thesis presents the **policy recommendations** and evidence for the shaping of new policy framework to enable economically sustainable development of wave and tidal energy technologies.

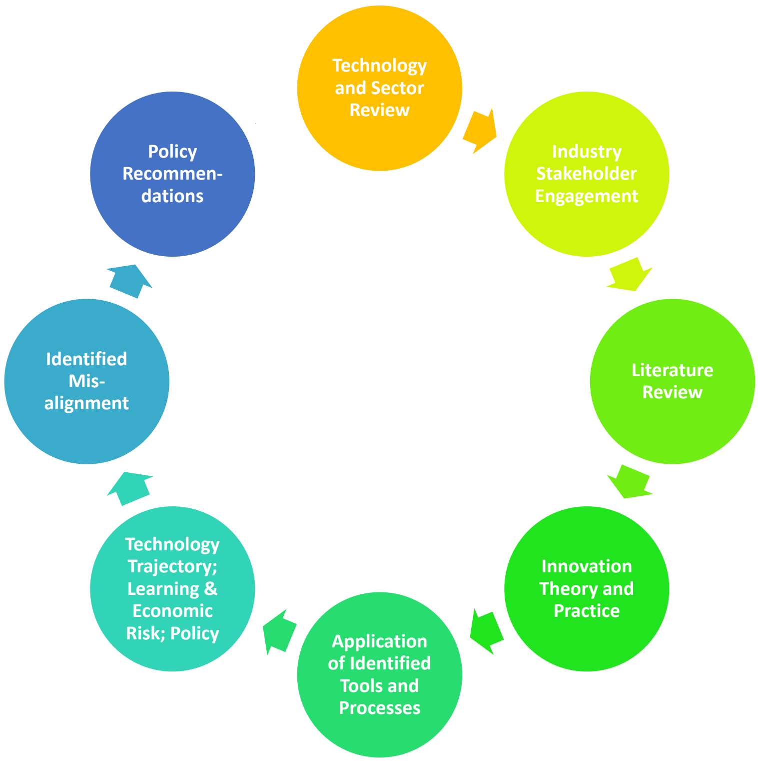

Figure 1.2: Thesis Summary Chart

Chapter 2

Technology and Sector Review

2.1 Chapter Introduction

This chapter briefly introduces the wider energy system that exists in the world today, and begins to investigate the role of wave and tidal energy sources in supplying electricity to contribute to increasing global demand for lower carbon energy. Wave and tidal energy technologies are not unique in terms of their need for investment to drive down costs, however the aim here is to provide the reader with a brief overview before digging deeper into the myriad of challenges that the ocean energy sector has faced, will continue to face, and indeed must overcome on the route to successful commercialisation of wave and tidal stream energy technologies.

2.2 The Energy System

Modern civilisation is irrevocably hooked on energy consumption: Energy is required for almost all activity, from transport fuels through to commercial and domestic electricity consumption and heat. Over the course of the 20th and 21st centuries, electricity has established itself as one of the most significant commodities (Fouquet, 2010), particularly within Organisation for Economic Cooperation and Development (OECD) countries. The transition from steam power to electricity involved a gradual process over a number of decades, between approximately 1821 and 1950 (Fouquet, 2010). Recent figures from the International Energy Agency (IEA) suggest that 22,688 TWh was produced globally during 2012 (International Energy Agency, 2014), representing a 270% increase over electricity production statistics from 1973 (the earliest records of global energy production from the IEA). Energy, in terms of both production and usage, is a topic with many challenges, risks and uncertainties.

Initial large-scale electrical power generation was achieved through the burning of coal, but several other power generation technologies also established themselves as core contributors to the energy mix in the mid-20th century, including hydro-electric, gas, and nuclear. Fossil fuels remain the dominant source of fuel for electricity production today. Indeed, 67.9% of global electricity production comes through the burning of fossil fuels (International Energy Agency, 2014). The largest source of renewable power generation comes from hydroelectricity, representing a sizeable 16.2% of global electricity production. The mid-twentieth century saw the emergence of nuclear fission as a source of energy that could be harnessed for power generation. Nuclear power now accounts for approximately 10.9% of global electricity production (International Energy Agency, 2014). Since its establishment, however, the risk associated with containment of radioactive waste, and, of course, the impact of global disasters such as Chernobyl and Fukushima – raising the awareness of the danger that presents itself when worst case scenarios occur – have led to increasing levels of public dissatisfaction with nuclear power, and uncertainty surrounds the role of nuclear energy in the global energy mix in many countries across the globe.

In recent years, new sources of renewable energy have emerged, paving the way for sustainable power generation. Wind energy and solar photovoltaic are considered to be the most mature of these newer renewable energy resources. In off-grid applications, these renewable technologies may already offer electricity production at a level cost competitive with diesel fuel generators, known as fuel parity (Breyer *et al.*, 2010). In addition, some of the more mature renewable energy technologies, when appropriately sited, may soon achieve grid parity, matching the costs of electricity generation from conventional thermal power plant (Breyer and Gerlach, 2013).

Increasing concern has been raised at the level of airborne pollution in some of the world's largest cities. In addition, greenhouse gas (GHG) emissions (in particular carbon dioxide) are now recognised, in both scientific and political circles, to be one of the dominant causes of environmental change – a situation that is becoming increasingly more difficult to mitigate. Decarbonisation of energy supplies is seen as a necessary route to facilitate a decrease in overall GHG emissions.

It is widely recognised that energy system change is necessary, and indeed must accelerate, particularly within the area of low carbon technological innovation (International Energy Agency, 2012; HM Government, 2011; Chiavari and Tam, 2011) in order to meet long-term national and international level legislation on climate change. Policies at a national level (European Parliament and Council, 2001; European Commission, 2009; Lewis and Wiser, 2007), and indeed renewable energy targets such as those set in the National Renewable Energy Action Plans of EU Member States (Member States of the European Commission, 2010), have been attempting to stimulate innovation in renewable energy technologies; policymakers are utilising a wide range of policy instruments including technology-push and demand-pull (market pull) support mechanisms (Nemet, 2009). Legally binding national carbon emissions reduction targets, such as the Climate Change Act 2008 in the UK (HM Government, 2008), have set high emissions reduction and sustainable electricity generation targets, but Governments across Europe are struggling to meet renewable energy objectives. For renewable energy technologies, this imperative for accelerated low-carbon innovation presents both an opportunity and a challenge: An opportunity, because policymakers and investors are willing to actively engage in technological innovation support where tangible and credible results can be identified; a challenge, because the drive for accelerated technological change brings a risk of unrealistic short term expectations.

When responding to these imperatives for change towards a low-carbon system within electricity generation, it is essential that there is recognition of different classes of renewable energy technologies. Amongst the myriad of technological options for renewable electricity generation, it must be appreciated that these are at different levels development and technological maturity, to a greater or lesser extent, and each technology presents different opportunities and risks. For example, onshore wind and solar photovoltaic (PV) technologies, often considered to be the most mature 'new' renewable energy technologies, have demonstrated notable cost reductions and achieved exponential market growth over the last few decades (Müller *et al.*, 2011; United Nations Environment Programme, 2012). While it is likely that wind and solar PV will contribute to the majority of renewable energy growth over the short and medium term, other, less mature, renewable energy technologies have longer term potential for development, commercialisation, and deployment. More recently, wind energy has progressed from onshore to offshore locations, and new forms of power generation from the sea have emerged, namely wave, tidal stream, salinity gradient and Ocean Thermal Energy Conversion (OTEC). Power generated through sea-based renewable energy sources is now commonly referred to as 'Blue Energy'.

As the global thirst for energy increases and fossil fuel reserves decline, mankind must search for opportunities to harness new and renewable energy sources to enable sustainable and environmentally acceptable provision of the electricity that is so often taken for granted. In order to ensure security of supply and long term economic, environmental and social sustainability of power generation, a wide range of generation technologies will need to be utilised.

2.3 Ocean Energy: Wave and Tidal

Over seven-tenths of the earth's surface is covered by water, of which oceans contain over 97% of the water by volume. Large bodies of water such as seas and oceans contain an abundance of energy in a variety of forms. The definition 'ocean energy' in the context of this thesis, however, includes only those that can be converted by wave and tidal stream energy technologies. Both wave and tidal stream technologies can be considered as analogous to wind farms, in the sense that many different sites can be exploited (at locations where suitable resource exists), and multiple modular devices cumulatively combine to achieve larger overall capacities. Tidal barrage technology (utilising tidal range – the vertical rise and fall of the tides) is considered to be a mature technology, exhibiting entirely different financial and environmental requirements to that of wave and tidal stream energy, and so barrage technology is not considered within the scope of this thesis. Similarly, OTEC and Salinity Gradient, while the subject of conceptual research, feasibility studies, and early prototype demonstration, are also beyond the scope of this thesis and are not considered. Wave and tidal stream energy conversion technologies are technology fields that have attracting considerable interest internationally (Mueller and Jeffrey, 2007; DECC, 2011), however, patience in the development trajectory of these technologies has been waning since 2014 at both a political and industrial level.

The two forms of ocean energy selected for this research present very different resource characteristics and challenges. Waves result from kinetic energy transfer from the wind to the upper surface of the ocean due to both friction and pressure. The total energy flux between the wind and the ocean surface, based on the strength, intensity and direction of the wind resource – in combination with the area over which the wind interacts with the sea surface (known as the fetch) – influence the characteristics of the resultant wave. Wave interaction creates a complex wave field, but characteristics such as significant wave height and period can be measured statistically from the resource. Wave energy is a derivative of wind energy (which in turn is a derivative of solar energy), but the wave energy resource has a greater power density over a given area compared to wind energy (Falnes, 2007).

Tides, unlike other forms of renewable power generation, are entirely predictable. Large bodies of water – such as oceans and seas – are forced into motion by the interaction between gravitational forces of the earth, moon and sun. This, in addition to the rotation of the earth on its axis, causes periodic movements and variations of the oceans and seas, known as tides. Vertical movement of the seas and oceans can be seen in the difference in water level at high and low tide, which is know as tidal range. Horizontal motion, or flow of water, is known as a tidal current.

2.3.1 Resource

It is recognised that there is a significant level of wave and tidal energy resource in a number of locations geographically. The ocean energy resource is considered here at three levels: Member State (UK), Continental (Europe), and global.

The UK has pioneered the wave and tidal energy sectors, with favourable support mechanisms emerging as a result of the increased recognition of the substantial quantity of resource available in UK waters. Studies suggest that wave and tidal energy could meet up to 20% of UK electricity demand (Black & Veatch, 2005; Carbon Trust, 2011). Figure 2.1 indicates the distribution of wave and tidal energy around UK shores.

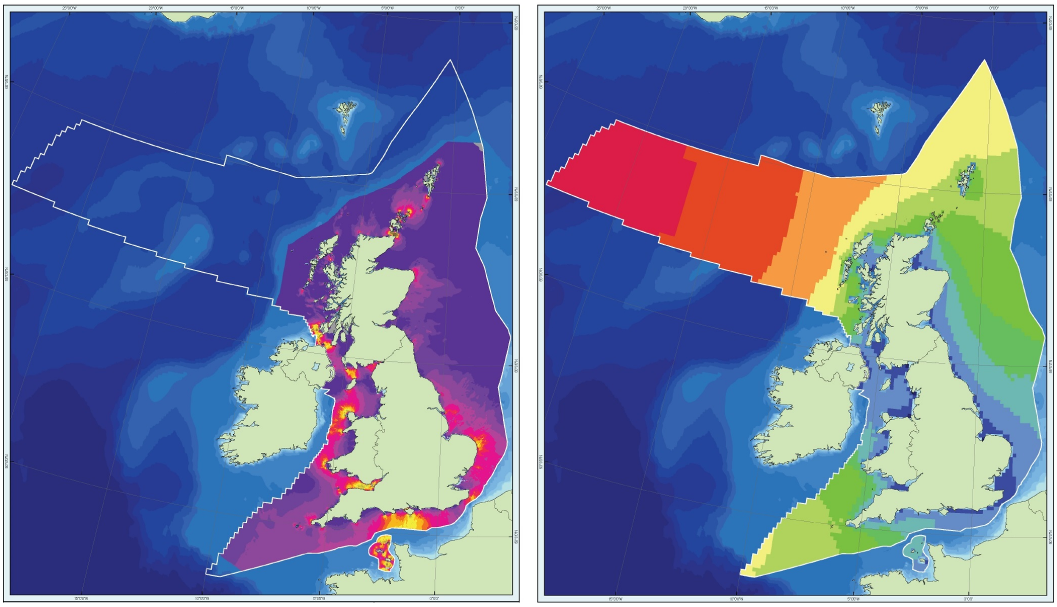

Figure 2.1: Mean Spring Tidal Power (left) and Mean Wave Power (right) in the UK (Source: (ABPmer *et al.*, 2008))

As indicated in the resource maps, strong tidal flows are located around the Pentland Firth, Orkney, and Shetland Islands in the north of Scotland, the English Channel and Channel Islands, west of Islay and the Mull of Kintyre between the Scottish mainland and Ireland, and also to the north west of Anglesey.

The wave energy resource is concentrated in the north-west of the UK – particularly west of the Outer Hebrides where there is exposure to large fetch and Atlantic swell. Although the wave energy diminishes the closer it approaches to shore, there are attractive levels of resource around the north-westernmost and south-westernmost areas of the UK, where there is no land mass shielding or obstruction to waves approaching from the predominant wave direction.

At a European level, the vast majority of the tidal stream resource is located around the UK and French waters. Additional areas of high tidal stream resource can also be found in northern Norway. Medium to low level tidal stream resource can also be found in certain locations on the coastline of Spain, and in the Straits of Messina between Italy and Sicily.

The strongest wave energy resource at a European level can be found on the west coast of the UK and Ireland, with additional strong wave energy resource on the Atlantic facing regions of EU member states – known as the Atlantic Arc. These resource distributions can be seen in Figure 2.2 and Figure 2.3.

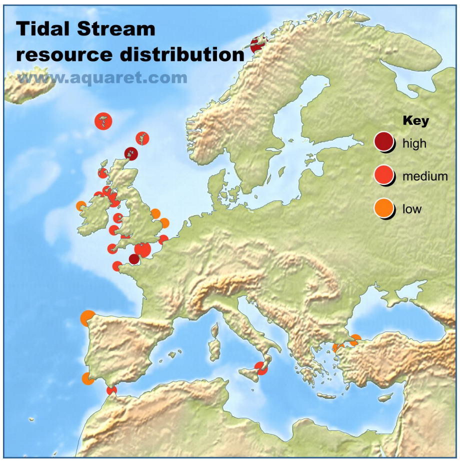

Figure 2.2: Tidal (AQUARET, 2013)

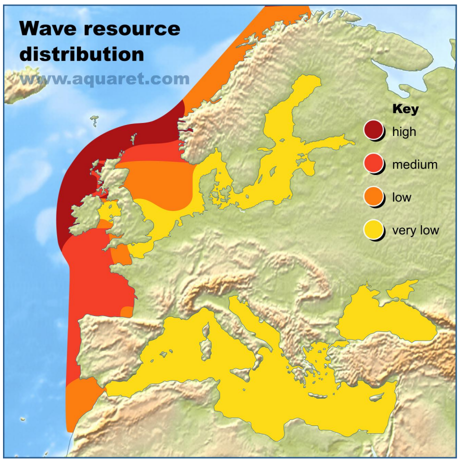

Figure 2.3: Wave (AQUARET, 2013)

Beyond Europe there are a number of other countries and regions that have significant ocean energy resources include North and South America, Russia, South East Asia and Australasia (Fraenkel, 2002).

While global tidal stream energy resource estimates vary, it has been reasoned that tidal stream energy could produce over 150 TWh/year globally (Black & Veatch, 2005). Tidal stream energy exists only in discrete geographical locations where the high current velocity required for economically attractive array projects are seen. In tidal energy, the dominant variable is the current velocity, and this single factor can have an impact on defining how attractive a certain site will be. While other parameters such as turbulence intensity, directionality, and wave influence will also impact device performance characteristics, it is the velocity that provides the dominant minimum requirement.

The energy contained within a wavefront is linked to the orientation of the local coastline relative to the open sea, the geographic lattitude of the wavefront, and the influencing wind speed and pressure factors that the wave has encountered over the fetch length. Wave energy resource is highly variable – with the main parameters of significant wave height (H_s), wave peak period (T_p), and wave energy period (T_e) varying both temporally and seasonally – creating significantly greater levels of uncertainty than exist for tidal stream velocities. Unique design challenges exist for wave technologies that will also vary depending on geographic location and associated resource.

It has been estimated that the wave energy resource is approximately 286GW in Europe, 242GW in North America, 547GW in Asia, 428GW in Africa, and 590GW in Australasia (Gunnar *et al.*, 2010). The global gross wave energy resource is estimated as approximately 3.7TW, with a net resource of 3TW once areas of low resource and seasonal ice coverage are removed (Gunnar *et al.*, 2010). The global wave resource can be seen to be heavily concentrated in the northern Atlantic Ocean and northern Pacific Ocean north of the Tropic of Cancer, and the South Atlantic, South Pacific and Indian Ocean south of the tropic of Capricorn, as shown in Figure 2.4.

It is clear that an abundant global resource exists, ensuring that any successful demonstration of technology would open up a wide market for deployment – for both wave and tidal stream technologies.

2.3.2 Ocean Energy – A Deployment Potential

It has been estimated that over 50% of the global population live within 60km of coastlines, and it is anticipated that migration towards coastal areas will cause this number to rise in the future (Harvey and Canton, 2010). It is therefore appropriate to recognise that ocean energy resources could offer an attractive opportunity for the delivery of electrical power, drinking water, and other potential by-products to coastal population centres.

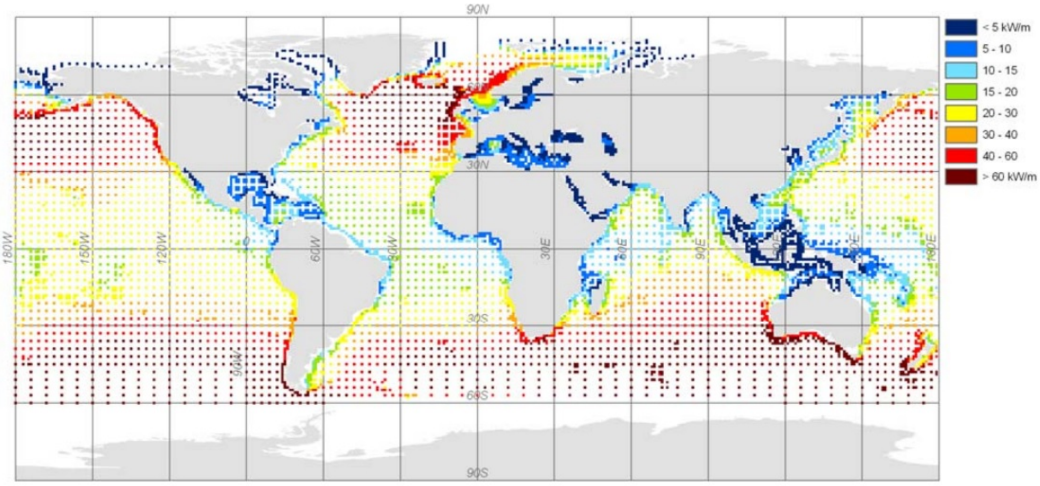

Figure 2.4: Annual Global Gross Theoretical Wave Power (Gunnar *et al.*, 2010)

According to the International Energy Agency, initial forecasts under favourable deployment scenarios estimate a potential of 337GW of ocean (wave and tidal) energy deployment by 2050 (Huckerby *et al.*, 2012); this vision presents a possible deployment scenario, generating 810TWh/year – enough to provide energy for over 230 million households (Huckerby *et al.*, 2012), but it is expected that ocean energy deployment would continue beyond this level in the longer term. At a national level, the UK's average practical wave and tidal resource is estimated at between 2 and 7GW (Blunden and Bahaj, 2007), however, it is admitted that there is great uncertainty in these resource estimates. The Scottish Government claims that 25% of the European tidal resource and 10% of the European wave resource exists around the coastlines of Scotland (The Scottish Government, 2014), and research has shown that UK wave and tidal resources could meet up to 20% of UK electricity demand (Black & Veatch, 2005; Carbon Trust, 2011). Although barriers to large-scale deployment still exist (Magagna *et al.*, 2014; MacGillivray *et al.*, 2013a), significant measures are being put in place at a European Commission level to identify and address the challenges. The implementation of an Ocean Energy Forum (European Commission, 2014a) and the establishment of the Technology & Innovation Platform for Ocean Energy (TP Ocean) aims to draw the marine energy sector together and bring solutions to the industry's common challenges (Ocean Energy Europe, 2014).

The wave and tidal energy sectors are pioneering development of devices to harness and capture the energy contained in ocean wave and tides. Both wave and tidal energy converters are at the cutting edge of engineering design. The commercial development of ocean energy technologies could demonstrate the fulfilment of two very important policy objectives: provision of secure low carbon energy, and the establishment of an attractive domestic and international export market for industry stakeholders. However, wave and tidal energy technologies are still in the nascent stages of development and demonstration. Existing devices are not yet cost competitive with conventional and more mature renewable energy technologies such as onshore wind (MacGillivray *et al.*, 2013a; Allan *et al.*, 2011), however it should be noted that wave and tidal energy technologies are not alone in their need for investment to drive costs down. A similar challenge is faced by the offshore wind energy sector, which although starting from a more competitive cost, must receive significant investment if cost competitiveness with onshore wind energy is to be achieved.

Pressure for accelerated development and deployment of new ocean energy technologies presents serious technical and financial challenges. The drivers and uncertainties that are already characteristic of the nascent ocean energy sector need to be more comprehensively understood. There is also an urgent imperative to understand the relative impact of these uncertainties on the management of appropriate strategies to enhance and accelerate both technology development and device deployment within both wave and tidal energy technologies. The wave and tidal energy sectors must prove reliable technology operation in addition to achieving substantial cost reductions in order to guarantee investment and to secure their place in future energy portfolios (House of Commons Energy and Climate Change Committee, 2012). There are significant barriers and obstacles to large scale deployment of technology capable of harnessing this ocean energy resource, but opportunities that could result from the resolution of existing barriers make wave and tidal energy very attractive technological possibilities for consideration within the future energy mix.

2.4 Wave and Tidal Energy – State of the Art

Wave energy and tidal energy are abundant natural renewable energy resources that are, by their very nature, highly complex; each resource exhibits very different characteristics and design challenges. Despite a vast global marine energy resource and previously high levels of interest from large multinational engineering corporations, wave and tidal-stream energy converters are still nascent technologies. Significant challenges remain before the new technology can reach its full potential. Several technologies have been trialled at test centres across the world in order to demonstrate the functionality and operability of ocean energy device concepts. Countries such as the UK, France, Canada and South Korea are actively pursuing large scale development of tidal energy projects - others could be on the cusp of following suit. Wave energy technology, due to technical and economic challenges, is somewhat behind tidal stream energy, and the focus is beginning to shift from multi-MW array deployment. However, a serious and concerted effort should be made to explore, and overcome, the current economic and technical challenges of artificial extraction of ocean energy, in order to provide credible pathways for future exploitation of these new energy technologies.

In the wake of the 1970s energy crisis, an increasing level of wave energy Research & Development (R&D) programmes were established (Cruz, 2008). The majority of the early ocean energy R&D took place within research institutes and universities (Falnes, 2007). A subsequent drop in the price of fossil fuels, together with an increase in favour for nuclear energy within many government policies, resulted in a reduced appetite for expensive new renewable energy technologies, and the interest in ocean energy research activity dwindled, providing very little innovation from the mid-1980s to mid-1990s.

However, in contrast to wave energy research, localised efforts directed towards wind energy continued: Serial production of small-scale (by today's standards) wind turbines began in the late 1970s - predominantly in Denmark where the government, driven by a desire to reduce energy dependency on imported fossil fuels and distinct public opposition for nuclear energy (Lipp, 2007), provided reliable financial support mechanisms for both development and deployment of wind power projects and prioritised grid connection of new wind farms over conventional power generation systems (Smith, 2011). With the maturity of onshore wind turbine technology and its establishment in many countries across the globe, a progression to larger turbines together with an attraction to the higher and more consistent wind speeds located offshore has opened up opportunities for development of wind farms located in shallow (up to circa 40m water depth) coastal waters. Solutions to deep water deployment of wind turbines are also being explored (Roddier *et al.*, 2010). Offshore wind energy will be a key technology in meeting existing European 2020 renewable energy targets – and market ready devices have already been deployed commercially in shallow water situations (4C Offshore, 2012).

Although wave and tidal energy converters are emerging technologies and face challenges on the route to commercialisation (Mueller and Wallace, 2008; Khan *et al.*, 2008), large-scale deployment could offer the same security of electricity supply, carbon dioxide emission reduction, and economic benefit that resulted from the development of the wind energy sector. The potential for these nascent technologies to play a key part in the future energy mix has long been recognised (Bedard, 2013; Pelc and Fujita, 2002). The early 2000's saw resurgence in the level of interest for wave and tidal electricity generation within research, industrial, and political circles; Governments worldwide are again considering large-scale ocean energy as part of a portfolio of methods for achieving carbon dioxide emission reduction and energy security, as well as seeing the potential for significant job creation and inward investment (Jeffrey *et al.*, 2013; HM Government, 2011).

Interest and activity from large multi-national engineering firms and utility companies such as Siemens, Rolls Royce, Alstom, Andritz, ABB, Vattenfall and Iberdrola allowed the ocean energy sector to consider progression from demonstration of a single device to installation of multiple device farms. Although significant project development work has taking place to help so called array projects become a reality, almost all of the early array projects appear to have reached a stalling point (MCT, 2013; ScottishPower Renewables, 2013). Spreading the cost of site development, environmental impact assessments, installation, power conditioning, and grid connection across a number of devices is substantially more cost effective than deployment of individual units in discrete locations; in addition, only array projects will be able to supply sufficient cumulative energy output to justify transmission and distribution costs and provide meaningful contributions to the local power supply. However, the above statements are only true of technology that is capable of affordable and reliable operation, meeting design specifications in the technology's intended deployment environment, at a price that can be economically justifiable, with a clear route to market.

A move from single device demonstration to array projects would signal assurance in technology reliability and survivability (demand for multiple unit orders will only come once potential customers are satisfied that the initial pre-commercial demonstration devices have shown suitable performance and reliability in operation), opening up opportunities for serial production of devices and growth in key component supply companies. Fostering the emergence of stable domestic market may pave the way for increased global adoption and export opportunities of a new technology (Lewis and Wiser, 2007), providing incentive to those with first-mover advantage to maintain commitment in continued technology development. Progression from single device to array development is also critical for the sector to meet existing ocean energy deployment targets; otherwise there is a risk that a failure to meet deployment targets would result in a loss of confidence in the ability of the ocean energy sector to deliver meaningful contributions to the electricity mix in the medium term. However, these goals are at risk of becoming over-optimistic and visionary if fundamental technology development does not allow the emergence of a successful candidate technology.

Test centres have allowed the demonstration of individual concepts - such as the Pelamis P2, Aquamarine Power Oyster, and Wello Oy Penguin wave energy converters, or the Alstom DeepGen, OpenHydro, Scotrenewables SRTT250, and Andritz Hydro Hammerfest HS1000 tidal energy converters (EMEC, 2012) but there remain further challenges in array deployment, such as the cumulative impact of multiple extraction points on the overall resource levels (how much cumulative energy can be extracted from waves or tides at discrete locations without significantly altering the wider extraction potential elsewhere) (Couch and Bryden, 2006; Palha *et al.*, 2010), and the development of optimal maintenance strategies to ensure minimum disruption to power production (King and Tryfonas, 2009). Reliability demonstration is a key activity for the developers of wave and tidal energy converters (O Rourke *et al.*, 2010; Ferro, 2006), as although many concepts exist, the next immediate challenge is to demonstrate continuous autonomous operation for prolonged periods of time.

Presently there is still a significant amount of technological fragmentation: There is limited commonality between different devices, and widespread design diversity is prevalent, particularly within the field of wave energy (Khan *et al.*, 2008; King and Tryfonas, 2009).

2.4.1 Tidal Energy Converter Technology

There are three principal hydraulic mechanisms in which tidal currents are suitable for energy extraction: Tidal streaming, hydraulic current and resonant basins.

1. Tidal streaming occurs due to the physical principle of continuity within a fluid flow: As water flows through a constriction, the flow is accelerated, maintaining continuity.
2. Hydraulic currents occur when two large bodies of water are connected, but due to the geospatial difference in tidal range (due to non-concurrent or out of phase tidal ranges) within each of the bodies of water, a pressure head is created. This pressure head results in a flow of water from one body of water into the other.
3. Resonant basins occur as a direct result of constructive interference between an incoming tidal wave and a reflected tidal wave. This physical situation results in the formation of a standing wave.

The dominant variable in defining the energy within a tidal stream is the velocity, as the power within a tidal flow is seen to be proportional to the cube of the velocity, shown in Equation 2.1:

$$P = \frac{1}{2}\rho A C_p u^3 \tag{2.1}$$

where P is the power in Watts; ρ is the density of the fluid (sea water), approximately $1025 kg/m^3$; A is the swept area of the rotor; C_p is the coefficient of performance of the rotor; and u is the velocity of the fluid flow.

For a technology developer, the motivation therefore exists to harness energy from sites where the velocity is large enough to enable economic deployment of technology. A one-seventh power law is frequently used to approximate the velocity profile with respect to water depth for a given tidal flow, however this is not necessarily a fully accurate representation of the true flow profile at all points during the tidal cycle. In reality, the velocity flow profile will be affected by both small and large scale turbulence, and geophysical conditions such as seabed roughness, bathymetry and surrounding land mass topography. The general equation for a power law is presented in Equation 2.2:

$$\frac{u}{u_r} = \left(\frac{z}{z_r}\right)^{\alpha} \tag{2.2}$$

where u is the tidal current (in metres per second) at height z from the sea bed; u_r is the known tidal current velocity at reference height z_r; and α is the exponent, an empirically derived coefficient commonly estimated to be $\frac{1}{7}$.

Tidal energy offers some advantages over other renewable resources such as wind and wave. The fluid medium, sea water, is over 800 times denser than air, so tidal power offers a greater energy density than wind for a given turbine rotor swept area. As the movement of tides result from gravitational forcing and the lunar cycle (see Figure 2.5), the tides flow with a predictable intermittency (Pugh, 1996). That is to say that the variability is deterministic (and not stochastic like wave or wind). This has the potential to ease the integration of tidal energy into existing electricity networks. Providing a sufficiently long data set exists (35 days is the recommended minimum duration (Iyer, A., 2011)), predictability of the tides is possible through a process known as harmonic analysis, a process discussed and outlined in the literature (Pawlowicz *et al.*, 2002; Hardisty, 2009). As a result of harmonic analysis, tidal velocities can be predicted

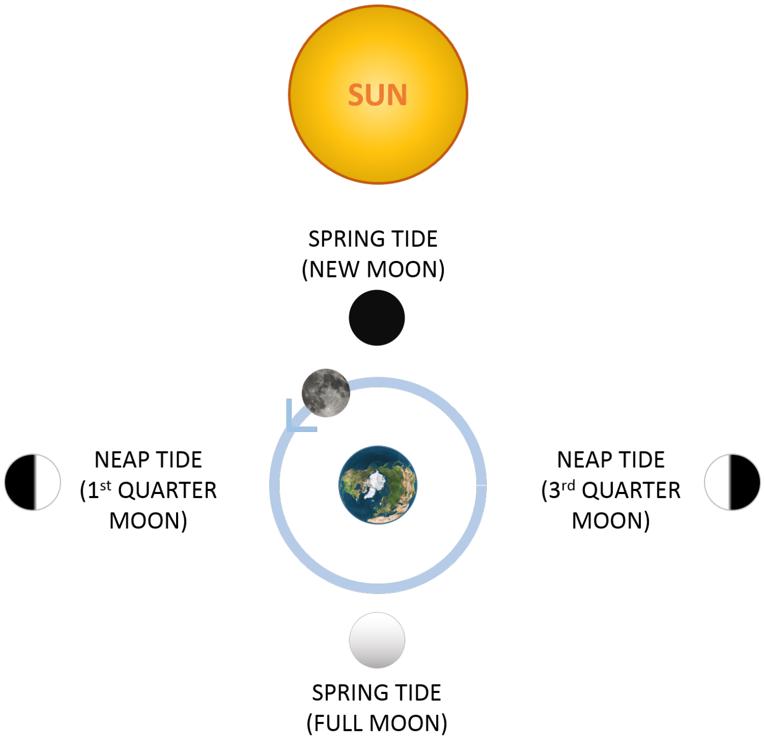

Figure 2.5: The Lunar Cycle and Impact on Tides

to a good accuracy indefinitely, both to the future and retrospectively. The kinetic energy within the horizontal motion of tidal currents, also known as tidal stream, marine hydrokinetic, and in-stream energy, has been the focus of much of the recent tidal energy research and development.

Although several conceptual energy extraction methods exist for tidal stream energy converters, the majority of the technology developers have converged upon a horizontal axis turbine design, similar to that adopted by the wind energy industry. Horizontal axis turbines are well understood from the wind sector and a range of components for horizontal axis machines already exist. It can also be noted that limitations of other designs have already been exposed within the wind energy sector, adding further incentive to the convergence on horizontal axis tidal turbines.

Foundation and Mooring Options

Securing devices so that the structure is able to resist the forces from the current is no simple task. Several concepts exist and, despite the relative convergence on to horizontal axis turbines, there is still considerable design diversity in the methods used to secure the device to the sea bed, as presented in Figure 2.6, where the structural foundation and mooring options can be defined as: fixed monopile (surface piercing) [1]; pin pile [2]; gravity base [3]; and moored buoyant [4].

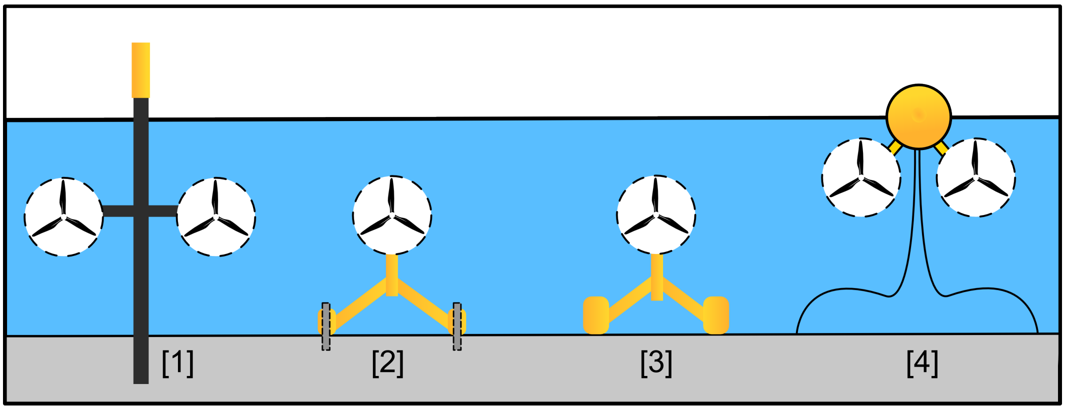

Figure 2.6: Tidal Turbine Foundation and Mooring Options (Source: (SI Ocean, 2012))

Horizontal Axis Turbines – MW Class

A number of technology developers have constructed and demonstrated pre-commercial prototypes for the testing and proving of tidal stream energy conversion technology, including horizontal axis and vertical axis turbines, and oscillating hydrofoils.

The majority of technology developers fall into the horizontal axis category, and a sizeable number of technology developers are focusing on technology in the MW class. Devices in this category tend to have rotor diameters in the order of 13-20m, but have a number of technical differences in drive-trains and rotor speed control. An example of a MW-class TEC is shown in Figure 2.7.

Figure 2.7: Andritz Hydro Hammerfest HS1000 (Andritz Hydro Hammerfest, 2016)

Horizontal Axis Turbines – kW Class

Horizontal axis turbines in the kW class follow very similar design principles as those in the MW class, however, fundamental differences in the corporate philosophy present a greater degree of emphasis on the proving of technology at smaller-scale prior to the rapid up-scaling that has dominated the wider tidal energy sector. An example of a kW-class TEC is shown in Figure 2.8.

Figure 2.8: Tocardo T2 (Tocardo, 2016)

Horizontal Axis Turbines – Multi-Rotor Platforms

Multi-rotor platforms are designed to accommodate two or more devices on a common mooring or foundation platform. Some designs are technology neutral, and permit the integration of a number of different device designs. Companies undertaking the design of such platforms often have experience within other sectors such as offshore oil and gas. The positive or neutral buoyancy of multi-rotor platforms allows devices to be supported in the upper section of the water column – the region of highest tidal velocity. The successful completion of model testing, concept demonstration at regional test facilities, and the award of leases at international test centres, will see the deployment of multi-rotor platforms in the near future. The installation of multiple rotors on a common mooring would open the door to significant cost reductions. An example of a multiple rotor platform with TECs is shown in Figure 2.9.

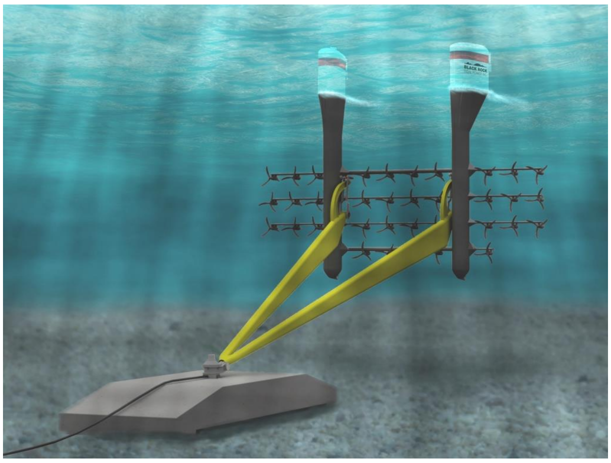

Figure 2.9: Multi-Rotor Platform: Tidal Stream Triton with Schottel STG50 TECs (Schottel, 2016)

Vertical and Transverse-horizontal Axis Tidal Turbines

Although less common, there are a small number of prototype tidal stream turbines utilising vertical axis or transverse horizontal axis designs, differing greatly from the horizontal axis turbines that form the mainstay of tidal energy converter technology development. Examples are shown in Figures 2.10 and 2.11.

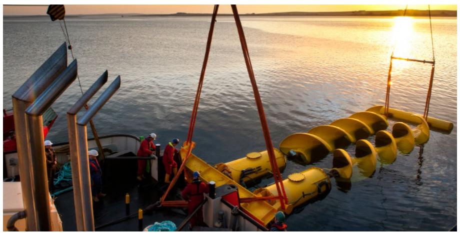

Figure 2.10: Vertical Axis TEC (Tidal Energy Today, 2015)

Figure 2.11: Transverse Horizontal Axis TEC (ORPC, 2016)

Radical Tidal Energy Concepts

Innovation within the tidal energy sector is pushing the boundaries of engineering. New concepts are opening up the possibility of commercially viable energy production from tidal flows previously thought to be uneconomical. The idea of a radical concept may challenge the fundamental principles of operation of a tidal energy converter, or it may look at revolutionary materials that have not yet been used within the sector. A radical concept must open up potential routes to significant step change cost reduction. Current 'first' generation concepts use sea bed mounted devices, but radical new concepts are looking to remove the need for large foundation structures, making greater use of buoyancy and tensioned cables. There are also some designs that are challenging the conventional horizontal axis turbine approach. These radical concepts may open up routes to significant step change cost reduction. By their very nature, radical concepts are not necessarily proven technologies, and may require significant development before a definitive judgement can be made on whether they do, in fact, reduce the cost of energy.

Scotrenewables have developed and demonstrated a 250kW floating tidal turbine (Figure 2.12), whereby two 125kW rotors hang from the underside of a floating cylindrical housing that also acts as the container for all electrical and hydraulic equipment. The design benefits of a floating turbine include significantly reduced installation and retrieval costs, which can improve Operations and Maintenance (O&M) costs considerably. It may also be possible to carry out replacement of small components on site, without the need to retrieve the turbines. The use of buoyancy is a significant feature of second generation tidal turbines, allowing the rotor to be located higher in the water column in order to access the higher flow speeds.

Nautricity have utilised buoyancy and contra-rotation in their Contra Rotating Marine Turbine (CoRMaT) in a novel way to reduce the loading on the structure and mooring systems (see Figure 2.13). The rotor torque from each set of rotor blades cancel out the effects of the other

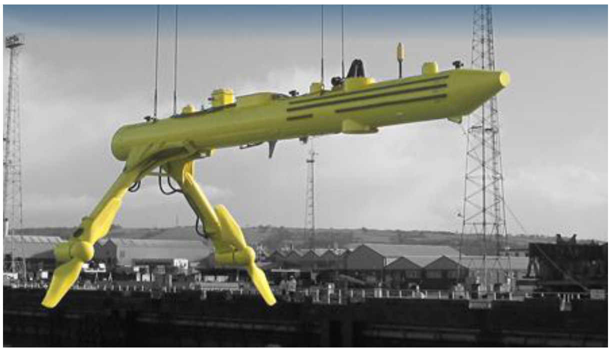

Figure 2.12: Scotrenewables SRTT250 (Scotrenewables, 2014)

rotor due to the each rotor spinning in a different direction on the same axis, leaving negligible net total torque from the turbine, thus allowing a single point mooring system to be used. The rotors have an unequal number of blades to ensure that the shadowing effect from the first set of blades does not cause adverse fatigue loading on the second rotor and remainder of the drivetrain. Nautricity are also developing HydraGlide, a surface float for the CoRMaT device that will allow the turbine to maintain an optimal position within the water column. The buoyant device also removes the need for large heavy lift vessels, significantly improving O&M costs and allowing greater ease of deployment and retrieval.

Figure 2.13: Nautricity CoRMAT (Nautricity)

The **Minesto** Deep Green concept has the potential to unlock deep water sites where there is only a modest flow velocity – sites that would not currently be considered economically feasible with existing horizontal axis turbines. A small turbine and generator are fixed underneath a wing structure (see Figure 2.14), which, utilising the effects of hydrodynamic lift, can accelerate the device through the water at speeds of up to ten times the flow speed of the surrounding water. ‘Flying’ in a figure-of-eight motion through the water, controlled by a rudder at the rear of the device, the concept is able to increase the relative velocity of water entering the turbine. The device can be tethered to the seabed, or to a moored floating structure such as a barge. In 2012, a one-tenth scale prototype was demonstrated in Strangford Lough, Northern Ireland, UK (Minesto, 2016).

Figure 2.14: Minesto Deep Green (Minesto, 2016)

The **Texel Project** is a joint initiative between turbine developers Tocardo and Schottel, offshore moorings specialist Bluewater, and shipyard Damen. They have combined their knowledge and expertise to develop a low cost solution for tidal turbines, suitable for deployment in remote locations, potentially even those without access to grid connection. The buoyancy unit consists of modular components, based on standard shipping containers, developed by Damen (see figure 2.15). A Tocardo T1 or T2 tidal turbine or Schottel STG50 would be mounted underneath the buoyant platform. The modular buoyancy unit would house the electrical equipment. The modularity and ease of transport associated with this concept lead to feasibility of transport via road, rail, or ship, to any location worldwide (Damen, 2016).

Design Convergence in Tidal Stream Energy Converter Technologies

Although several principal extraction techniques exist for harnessing tidal energy (AQUARET, 2013; EMEC, 2013b), recent times have seen the demise of a number of concepts on economic and technical performance grounds. Both the oscillating hydrofoil design demonstrated by Pulse Tidal (which strongly resembles an earlier failed 150kW Stingray device, which had been trialled by The Energy Business in Yell Sound, Shetland (Tidal Energy EU)), and the vertical axis Proteus prototyped by Neptune Renewable Energy, experienced troubles forcing the developers into bankruptcy (OffshoreWIND.biz, 2014; Tidal Today, 2014). While this

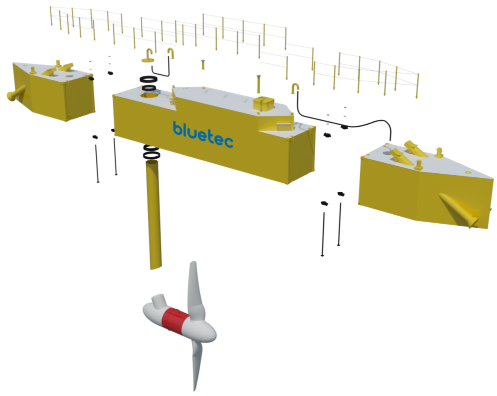

Figure 2.15: Modular Tidal Energy Deployment (Damen, 2016)

may be disappointing news to many within the sector, the elimination of weaker technology reveals a process of technology shakeout and convergence on the front-running technology – the horizontal axis turbine. While a number of technological differences still exist within the horizontal axis category (for example foundation or mooring options, number of blades per rotor, fixed pitch or variable pitch blades, drive-train with gearbox/generator or direct drive Permanent Magnet Generator, yaw capability or fixed yaw, etc.), there has been significant design convergence giving enhanced credibility and confidence to the horizontal axis design. The majority of developers within the tidal industry favour the horizontal axis design, but there is still opportunity for optimisation of sub-systems allowing the dominant design principles to emerge.

2.4.2 Wave Energy Converter Technology

At a simplified level, wave energy technology can be located either on-shore, near-shore or offshore. Wave energy converters can also be designed for operation in specific water depth conditions – deep water, intermediate water or shallow water. The fundamental device design will be dependent on the proposed location of the technology (in terms of water depth) and the intended resource characteristics into which the device will be placed. The different water depths can be defined as follows:

- **Deep Water:** Water depth is greater than one-half of the wavelength.
- **Intermediate Water:** Water depth is greater than one-twentieth but less than one half of the wavelength.
- **Shallow Water:** Water depth is less than one-twentieth of the wavelength.

The energy contained within the waves manifests itself in the form of kinetic energy (energy of the mass-movement) and potential energy (energy associated with changes in elevation, and hydrostatic/hydrodynamic pressure). As described earlier, wave energy is a derivative of wind energy – the kinetic energy from the wind is imparted to the waves through surface friction and pressure. This influences the orbital velocity of the water particles (kinetic and potential energy) and causes periodic variations in the free-water level at a given spatial reference point, and variations in hydrostatic and hydrodynamic pressure. The particle motion within the waves also varies relative to the water depth between the surface and seabed, and also how deep within the water column the particle motion is located. In deep water environments, water particle motion is circular, and the celerity (the horizontal velocity at which the wave propagates) depends on the wavelength alone – it is not impacted by the sea bed (Chella, 2016). Wave breaking can occur in the deep-water environment, when the wave steepness (a ratio of wave height to wavelength) exceeds a stable limit. The onset of wave breaking is driven by a number of possible mechanisms including dispersive focusing (when leading waves of a wave group have a higher frequency than following waves, and any positive interference between the waves of the wave group could lead to local wave breaking), modulational instability (deviations from the principal wave period are induced by the presence of non-linearities, which can result in the breakup of the original wave into a train of pulses (Brooke and Feir, 1967)), wind forcing (wave peaks can be locally forced by gusts or high wind speed), and wave-current interaction. The presence of currents opposing the direction of wave propagation decreases the wave steepness limit at which breaking will occur; currents following the direction of wave propagation increases the wave steepness limit at which breaking will occur (Perlin *et al.*, 2013).

As waves approach the shore, the depth to wavelength ratio decreases. In intermediate water, the celerity of the wave is impacted due to interference between water particle motion and the sea bed, and the celerity then depends on both the water depth and the wavelength (Chakrabarti, 1987). As the water depth decreases further, the wave velocity decreases due to increased interaction with the seabed and associated energy dissipation. The resultant effect on the wave is an increase in wave height and particle velocity at the wave crest, and a reduction in the wave length and celerity, causing the upper part of the wave to propagate at a larger velocity than that of the lower part of the wave. Deformation of the wave crest will continue until the wave steepness exceeds a stable limit, causing the wave to break(Chella, 2016). The process of waves breaking is complex, and involves a two-phase flow process in which the air-water interaction has a strong influence (Chella, 2016). The water particle motion within waves is represented diagrammatically in Figure 2.16. The deep-water wave orbital particle motion decreases exponentially with increasing water depth, which can be seen in the reducing path size for water particles deeper within the water column.

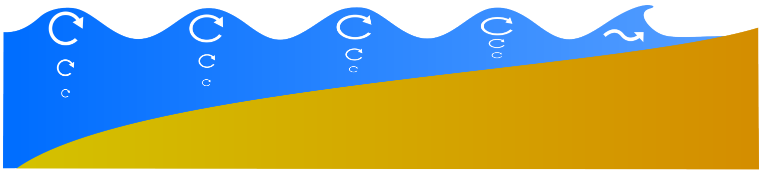

Figure 2.16: Water Particle Motion in Waves (Source: (SI Ocean, 2012))

The near-shore environment could perhaps be considered more accessible than the deep water environment, but still allows access to a significant extractable wave energy resource. The near shore environment is shielded from the largest ocean waves, and more directional waves are established with regards to force in the surge direction. As waves approach the shore, the wave speed and wave length decrease, resulting in an increased energy per unit area, known as wave shoaling. On the other hand, there is a lower resource in the near shore wave environment compared to deep water, as energy is lost due to drag with the seabed and wave breaking.

Much of the European ocean wave energy resource lies in deeper waters. The level of energy contained within the wave resource increases predominantly alongside increasing westerly distance from shore (AMEC Environment & Infrastructure UK Limited, 2012). Technological and financial limitations currently restrict the depth to which deployment can take place, but emerging technologies may open up markets in water depths of greater than 250m.

In order to quantify the available resource at a given location, site characterisation will form an essential part of the development process. IEC TS 62600-101:2015 provides a Technical Specification of the appropriate methodology for carrying out this task (International Electrotechnical Commission). Data collection can be achieved through the deployment of wave buoys or through use of land based wave radar systems. In ideal circumstances, a minimum of two to three years of wave data could allow for a reasonable first estimation of the wave climate at a particular site, however a larger data set containing ten years of wave data measurement would provide a more accurate estimation of extremes and long term climate statistics.

A significant challenge for technology developers within the wave energy sector is to demonstrate the survivability of a device. In a wave environment, the ratio of extreme loads to average working loads is high. A technology must therefore be over-engineered in comparison to the expected average operating conditions, in order for the mechanical and electrical components to survive the extreme loads that would occur during storm conditions. The characteristics of a good WEC include high conversion efficiency (high capture width – defined as the ratio of absorbed wave power (in kW) to the wave resource (in kW/m)), survivability (ability to operate efficiently, maximising energy capture within defined wave conditions, but shedding loads during extreme events thus limiting damage to the structure) and an ability to operate in a degraded mode to allow energy capture even under partial failure, thus facilitating adequate maintenance intervals.

The fact that the wave resource is not temporally aligned with wind energy peaks and troughs allows complementarity of the technologies – a combination of wave energy and wind energy could be used to create a smoother aggregated power output (Hart *et al.*, 2012).

A number of different conceptual technologies exist for harnessing wave energy; these technologies can can be classified by 'type' according to the means by which the device is designed to extract energy from the unique characteristics of different wave resources (SI Ocean, 2012; King and Tryfonas, 2009; EMEC, 2012; AQUARET, 2013). A number of these wave technologies will now be discussed in the following section of this thesis, however, it should be noted that the list of technologies considered is not exhaustive.

Oscillating Water Columns (OWC)

Oscillating water column (OWC) technologies make use of a structural chamber that is part filled with water. As the wave height varies with the oncoming resource, this variation in the water surface level is used to hydraulically pump a volume of air contained within the chamber through a self-rectifying air turbine – a turbine that rotates in one direction regardless of the direction of the air flow. When the water level decreases, the air flow reverses and air is drawn into the chamber, which again drives the turbine. OWC devices can be contained within a fixed structure at the shoreline, as shown in Figure 2.17, located in the near-shore environment as a sea-bed mounted structure, contained within an artificial man-made breakwater, or can be moored in deeper water as a floating system.

Figure 2.17: Oscillating Water Column: WavEC Pico Plant (WavEC, 2016)

Oscillating Wave Surge Converters (OWSC)

Oscillating Wave Surge Converters (OWSC) make use of the horizontal back and forth motion of the waves, generally in a near shore environment where the surge forces are accentuated by the ellipsoidal motion of the water particles. Structures can be hinged at the sea bed, and the structure is caused to oscillate by the motion of the waves. Power Take Off (PTO) systems for extracting energy from the oscillatory motion include hydraulic pumping of water to shore based Pelton turbines, or hydraulic or electrical PTO located on the converter itself. Floating variations of the OWSC device are also currently under development. An example of an OWSC can be seen in Figure 2.18.

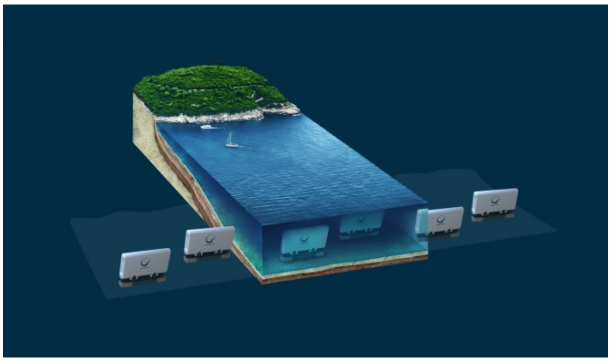

Figure 2.18: Oscillating Wave Surge Converter WEC: AW Energy Waveroller (Waveroller, 2016)

Point Absorbers

Point Absorber type devices utilise the upwards forces associated with buouancy to induce a heaving motion of one body relative to a secondary fixed body. The fixed body may be moored to the sea bed, or anchored through use of a large foundation mass. Point absorbers are considered to be non-directional, as the devices are capable of responding to incoming waves from any incident angle. An example point absorber is shown in Figure 2.19.

Figure 2.19: Point Absorber WECs: Carnegie Wave Energie CETO (Carnegie Wave Energy, 2016)

Attenuators

Attenuator type wave energy converters are generally multi-body devices. The incoming wave induces an oscillatory motion between two (or more) adjacent structural components. Attenuator type wave energy converters can be surface floating or fully submerged, however the former is most common in concepts that have been investigated to date. Attenuators are generally designed to yaw automatically to face the predominant wave direction (known as 'weathervaning'). Operational experience of long-body attenuators has also shown that these devices are susceptible to currents, which can cause deviation from the optimal alignment of the device relative to the approaching wave front. An example of an attenuator type wave energy converter is shown in Figure 2.20.

Figure 2.20: Attenuator WECs: Pelamis Wave Power (European Marine Energy Centre)

Overtopping / Terminators

Overtopping or terminator devices extract energy from the waves by channeling them to spill over a sloped collector into a reservoir that holds the water above sea level. The kinetic and potential energy from the waves is absorbed and stored within the reservoir. This creates a low head of pressure, from which energy can be extracted by using low-head hydro electric turbines. Overtopping devices have to be carefully designed to maximise the amount of water that spills over into the reservoir. Conceptual designs have considered both fixed coastal structures and moored devices that are designed to remain as stationary as possible within the more energetic water waves further from shore. An example of an overtopping / terminator device is shown in Figure 2.21.

Figure 2.21: Overtopping device: Wavedragon (Wave Dragon, 2005)

Rotating Mass

Rotating mass devices are caused to cause pitch and roll in response to the incoming wave energy resource. The structural body may contain an eccentric mass, which will become excited under the forcing of the motion of the structure, causing it to rotate. The rotation will drive an electrical generator contained within the device. A different permutation of the rotating mass device uses gyroscopic effect. An example of a rotating mass wave energy converter can be seen in Figure 2.22.

Figure 2.22: Rotating Mass WECs: Wello Oy (Wello Oy, 2016)

Radical Wave Energy Concepts

There are some innovative new concepts emerging in the wave energy sector, and some innovations that have been under development for some time. The idea of a radical concept may challenge the fundamental principles of operation of a wave energy converter, or it may look at novel materials that have not yet been used within the sector. A radical concept might open up potential routes to significant step change cost reduction. By their very nature, radical concepts are not necessarily proven technologies, and they may not be fully functional demonstration prototypes.

One such radical concept in the wave energy sector is the Anaconda, a device being developed by Checkmate Seaenergy (see Figure 2.23). Anaconda uses bulge wave technology, a concept that does not fall under any of the previous wave energy device types discussed. The device is essentially a large rubber tube filled with water, moored to the sea bed. Anaconda will float just below the surface of the water, and will align itself to face the incident wave direction. As a wave passes the device, the rubber tube will lift and become squeezed by the surrounding wave, and a 'bulge' of water will form within the rubber tube. This bulge will travel the length of the device, gathering energy from the wave as it progresses through the tube. Resonance can be achieved by ensuring that the speed of the bulge wave is identical to the speed of the forcing ocean wave, this ensures that high power capture is achieved. The bulge wave will drive a generator located at the stern of the device. Anaconda has been through a rigorous testing procedure at scale, providing proof of concept, at QinetiQ's Haslar Marine Technology

Park at Gosport, Hampshire. The next phase of development will require significant funding investment in order to produce a larger scale prototype. A "full-scale" Anaconda is anticipated to be around 200m long, with a diameter of 5.5 m and power output of 1 MW.

Figure 2.23: Checkmate Seaenergy Anaconda concept (Checkmate Sea Energy, 2016)

Another concept that has redefined the way in which developers can approach wave energy technology development is the AlbaTern Squid device. This concept consists of a central buoyant "absorber" linked to three arms, each with a surface float (see Figure 2.24). The relative motion between the central absorber and the link arms is used to pump hydraulic fluid. The PTO equipment housed within the device is rated at 7.5kW, making the Squid device significantly smaller than many other wave energy technologies under development. By utilising multiple Squid units in an array, known as "WaveNet", enhanced cumulative capacities can be reached. The current scaled device has been demonstrated at an off-grid location, providing power to a fish farm near the island of Muck. A number of other deployments of units at this scale are also planned. Future development will see a gradual up-scaling of the technology, which is distinctly different from the large scale prototypes being trialled elsewhere. The radical aspect of this technology is in the development pathway. While still expensive in terms of cost per kW, the Squid device can be constructed, transported, installed, tested, and operated at a fraction of the cost of larger concepts. The device itself also exhibits characteristics of attenuator, point absorber and terminator devices, without falling under any one definitive category.

Figure 2.24: Albatern Squid 7.5kW WEC (AlbaTERN, 2016)

Following on from a review of existing wave energy technologies, SBM Offshore, a company actively engaged in the offshore oil and gas sector, has pursued development of a novel wave energy converter which utilises an Electro-Active Polymer (EAP) material as the core structural component of the device (see Figure 2.25). The device is tubular in shape, with sealed end caps. The structure is slightly pressurised through being filled with water. The device remains neutrally buoyant just below the water surface. Waves passing over the outer surface of the device excite the water particles within the structure, generating bulge waves which repeatedly stretch and compress the structure. This novel approach has resulted in a concept in which the structural material is also the core PTO. The principle behind EAP material is that deformation in the structural shape of the material through tension and compression results in a change in capacitance of the material. The resulting deformation allows power extraction across the entire length of the device. Testing of the concept has been carried out in Nantes, with results being presented within conference proceedings of OMAE 2013 (Babarit *et al.*, 2013).

Figure 2.25: SBM S3 WEC (Babarit *et al.*, 2013; Wyllie and Newport, 2014)

In addition, multinational collaborative research is taking place using Dielectric Elastomers (DE), a class of EAPs which induce a changing electric field through deformation of the DE. The PolyWEC project has generated a number of conference and journal papers presenting the findings of research in DE systems (PolyWEC, 2016).

Lack of Design Convergence in Wave Energy Converter Technologies

A large number of concepts have been proposed in order to harness the energy in the waves. Some have proved to be conceptual or technological failures. Others being demonstrated have proven to be uneconomic for progression on to larger arrays or further prototypes – and have led to the demise of a number of wave energy technology developers such as Oceanlinx, Wavebob, Wavegen, and Pelamis. The technologies that have progressed to "full-scale" demonstration represent a range of technology options. Unlike tidal energy, wave energy has not achieved the same convergence and consensus towards an optimal design. The wave energy resource is more variable than the tidal resource, and a number of concepts exist due to the design optimisation around very different wave height and period. Furthermore, the ratio of peak loading to average loading is far greater in wave energy, with several different concepts each offering different solutions to the engineering challenge that this high extreme loading regime presents. While at a system level the best performing technology design is still to present itself, at a sub-system level there is acknowledgement that commonality and design consensus would open up routes to cost reduction and technical progression – as has been demonstrated with the recent funding announcements from Wave Energy Scotland (Wave Energy Scotland, 2015a).

2.5 Ocean Energy's Future

Ocean energy is still an emerging sector, and there still exists significant opportunity to influence the pace and the direction of wave and tidal energy development. The sector must be able to secure innovation and development funding, and demonstrate an increase in the level of technology deployment. Although ocean energy faces a number of technical, financial, and political challenges on the path to commercialisation, there remains the prospect that this emergent sector can make a significant contribution, by 2050, to the threefold opportunity for carbon dioxide emissions reduction (saving up to 0.8 billion tonnes of CO_2), providing security in electricity supply (annually generating over 810TWh of electricity through the deployment of 337GW of ocean energy capacity), and creating an industry capable of providing job creation and growth at a global scale (directly creating up to an estimated 300,000 jobs) (Huckerby *et al.*, 2012). It is clear that technology development and innovation still has a major role to play for the ocean energy sector.

2.5.1 Where the Sector Thought it Would Be

The emergence of an industry has been the vision of the wave and tidal energy sector for a number of years. Initial deployment targets for ocean energy were set in 2010 as part of the National Renewable Energy Action Plan (NREAP) for a number of EU Member State countries. 2020 wave and tidal energy deployment targets included 1,300MW of wave and tidal energy in UK, 500MW of wave and tidal energy in Ireland, 250MW of wave energy in Portugal, and 100MW of wave energy in Spain. A healthy industry in Europe was assumed to emerge with over 3GW in the deployment pipeline.

2.5.2 The Reality

Over-optimistic deployment targets have eroded confidence in the ability of the sector to deliver upon its promises. At both a technology development level and a policy target level, the upward revision of planned deployment dates and the downward revision of overall deployment targets has become a trend. The expense associated with technology development has resulted in a number of companies entering administration, or the divestment of ocean energy technology from a companies' technology portfolio (BBC, 2014; Kennedy, 2014).

Large scale marine energy deployment will not be part of a future energy mix through the actions of one country alone. International deployment, international development, and international collaboration will be required to ensure that the right investment support reaches the right projects at the right time. The challenges are not insurmountable, and the rewards on offer are substantial. Progress to date has delivered technologies that were believed by many to be on the cusp of volume production; however, recent challenges and setbacks have highlighted that the challenge of delivering a successful commercial ocean energy sector is far from over.

2.5.3 An Introduction to the Challenges

Engineering

A significant challenge for both the wave and tidal energy industries is to demonstrate the survivability of devices. The marine environment is harsh, with high loading (stresses and forces applied to the structure by the ocean current or waves) experienced by all wave or tidal devices in their regular operating regime, further compounded by extreme loading events during storm conditions. Certain aspects of device loading can be predicted, but there are also further challenges such as the performance of devices located in the wake, or 'shadow', of upstream devices, and the effects of extreme loading on devices, foundations, and moorings, all of which are still an active area of research.

A number of engineering challenges exist and underpinning topics such as reliability, survivability, maintainability, affordability, predictability and manufacturability have been discussed within literature, summarised as "ilities" (Mueller and Jeffrey, 2007). These "ilities" have also been utilised by Wave Energy Scotland in the definition of target metrics for funding programs, in which projects must demonstrate viable progression within each metric in order to be considered eligible for progression into future funding rounds. While many challenges remain to be addressed, they can be seen to largely fit under four key headings: performance, availablity, affordability and survivability, as shown in Figure 2.26.

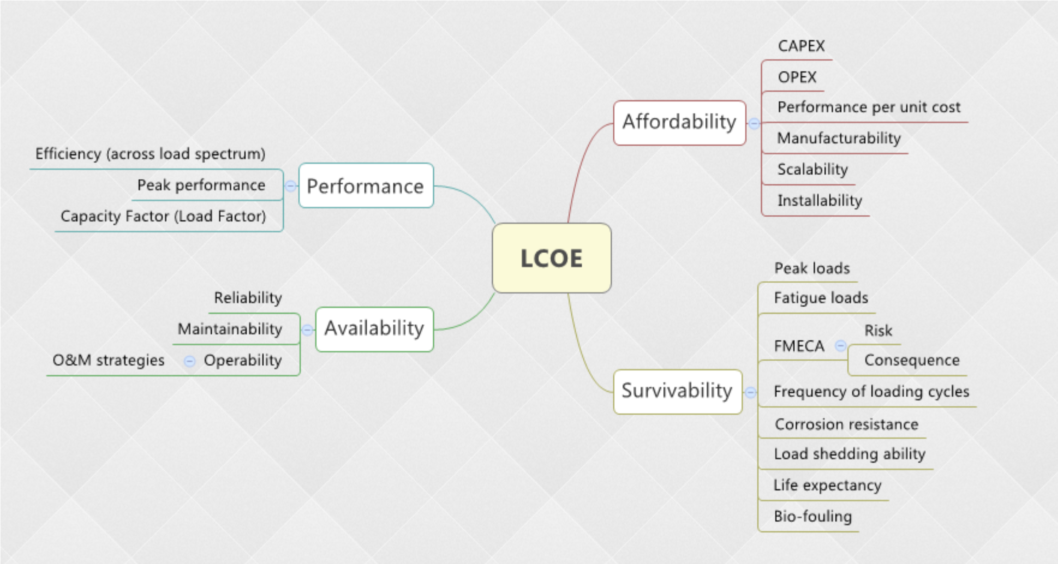

Figure 2.26: Engineering Challenges and Metrics for Ocean Energy Development

The **reliability** of a technology is the probability and level of confidence in the device/component to perform its function to design specification without interruption to operation. High component reliabilities will be expected where downtime would cause substantial detriment to overall system availability. Demonstration of reliability will take place over a number of operating years, with increasing levels of operational testing raising confidence in component reliability. Reliability impacts several other factors such as availability, and is of particular importance when considering operation within the harsh marine environment.

The **maintainability** of a device/component relates to the ease in which maintenance, repair or replacement can be undertaken in order to restore a device to full operational status. This considers the time requirements to retrieve and repair, and the time requirements to reinstate. Accessibility of device, components and sub-components will play a significant role in the maintainability of technology. Components must be designed for ease of maintenance, particularly when the risk of downtime has such a detrimental effect on the economic performance of the wider system.

The **performance / efficiency** of a device or component relates to the percentage of the input energy that can be successfully exploited through the conversion process intrinsic to that device or component, across its entire operational loading range. Performance is likely to vary across the range of operating parameters, and comprehensive understanding of this performance variation must be demonstrated. The performance, or efficiency, is a ratio of output to input.

The **survivability** of a technology is its ability to withstand extreme loading events and high fatigue cyclic loading. Demonstrating survivability must include proof of endurance of very high duty cycles and large frequencies of component cyclic loading. This metric also includes how the device or component is able to shed loads during extreme events, and how it can withstand the challenges associated with operation in the harsh marine environment such as duty cycle, bio-fouling and corrosion.

The up-front capital expenditure (CAPEX) and ongoing operations and maintenance expenditure (OPEX) will define the **affordability** of ocean energy projects. CAPEX refers to the up-front costs to design, build, install and commission a project. Ongoing costs throughout the project lifetime (£/annum) comprising of maintenance, operation, insurance, lease, and grid transmission and use of system charges are OPEX costs that can vary depending upon the location of site, and the nature of the technology employed (i.e. fixed, floating, bottom mounted, etc.).

The **manufacturability** of a device or component is the ease in which the design can be fabricated using existing tools and techniques. Greater manufacturability results in less complex construction and fabrication costs, and shorter fabrication times. The suitability of the component for mass manufacture will also impact on the overall level of manufacturability associated with the design.

The **installability** of a device or component relates to the ease in which it can be installed within a wider system, or brought to station where deployment is to take place. This metric also includes the transportability of the device or component from its point of manufacture to the point of end use. Installability may also be directly linked to affordability, as economic considerations must be made in the early stages of design.

Integratability represents the ease at which the system or components can be integrated with other sub-systems, across multiple device platforms, into a complete technology solution. It is also an indicator of whole-system integration with wider grid infrastructure, in which case is represented by the quality of the power output from the system.

The **scalability** of a device or component relates to the physical ability of the technology to scale appropriately and deliver the intended requirements in terms of output performance characteristics. This metric also seeks suitable intermediate steps prior to the engagement of full-scale testing and deployment in the open ocean, which could result in significantly de-risked technology proving.

Social and Societal

There is a role for improved engagement between device developers, the component supply chain, and research facilities. This can be achieved through funding bodies working together to submit joint calls for funding, targeting partnerships between academic and industrial facilities in a consortium to ensure that knowledge transfer take place at a sector wide level.

Market & Financial

Although the prize is attractive, the solutions for successfully harnessing ocean energy at a cost that is both affordable and sustainable have yet to be found. At a Member State and European level, funding mechanisms such as the Marine Energy Array Demonstrator (MEAD) (HM Government, 2014), Marine Renewables Commercialisation Fund (MRCF) (Carbon Trust, 2014), the French Environment & Energy Management Agency (ADEME) call for expressions of interest for marine energy (ADEME, 2015), national Feed-in-Tariffs (FiTs) across a number of member states, and the European Commission's New Entrants Reserve (NER300) fund (European Commission, 2014b) are targeting specific investment in the nascent ocean renewable energy sector to develop the first multi-MW arrays. However, these mechanisms have not provided sufficient leverage to enable many of the existing early ocean energy projects to reach financial close: The technologies that are at the perceived forefront of the sector have not yet reached a stage of development whereby there is sufficient confidence in the technology to generate the additional investment required from the private sector (Magagna *et al.*, 2014).

The investments from venture capital funding sources (that fuelled the early sector development) now form only a small portion (<10%) of the total ownership distribution for full scale prototypes (Løvdal and Neumann, 2011). The remaining funding requirements must be met by public and/or private sector investment in addition to any equity investment made by the device developer internally or by other organisations with direct involvement in a given project (Assmann *et al.*, 2006). Utility companies in search of reducing the cost of generating electricity are pulling out of high risk ocean energy projects (Macalister, 2013; Nichols, 2013).

Intellectual Property

Investment in specific technology developers by Original Equipment Manufacturers (OEMs) has brought commercial sensitivity issues that present barriers to knowledge transfer within the industry (MacGillivray *et al.*, 2013a).

Cost Reduction

Technological innovation is pivotal in the development of these emerging ocean energy technologies in order for cost reduction targets to be met and large scale commercial deployment to progress (Magagna *et al.*, 2014; Carbon Trust, 2011; Mueller and Wallace, 2008). However, the deployment of ocean energy will only be realised if the cost of energy from wave and tidal technologies can reduce to a level that is competitive with alternatives (MacGillivray *et al.*, 2013b). Already, revised 2020 ocean energy deployment targets (reduced from the initial NREAP projections) have been set within the UK (European Commission, 2014a; RenewableUK, 2013), and a number of other Member States. The rate of progress in ocean renewable energy has not matched the pace that was initially envisaged for the sector (Magagna and Uihlein, 2015).

2.6 Industry Stakeholder Engagement

The industrial applicability of this research was enhanced by ocean energy stakeholder engagement, the aim of which was to provide a means of identifying where, from the perspective of industry, challenges that remained to be addressed could form the basis of further research activity in alignment with the overall goals and objectives of this thesis. Engagement with ocean energy stakeholders ensured that this research is firmly grounded in the opinions and needs of the ocean energy industry. Stakeholder interviews and attendance at a supply chain focused workshop enabled a diverse range of views and experience to be collected and analysed, resulting in the identification of the key gaps in knowledge and the barriers to commercialisation that are inhibiting development and deployment of ocean energy technology.

The focus of the stakeholder engagement was placed on technology developers, project developers and supply chain companies across a range of countries within the European Atlantic Arc. It was recognised that different sub-groups within the stakeholder engagement have differing priorities, which is reflected in the decision to consider the views and opinions of each in order to generate a holistic overview of the sector.

Initial correspondence took place with industry representatives, where a brief questionnaire, consisting of 25 high level questions, was sent to targeted company representatives, together with a request for an opportunity to discuss the questionnaire at a face to face interview. From initial consultation, a total of 20 companies agreed to participate in face to face interviews. Each interview lasted between one and two hours. While the specific list of companies represented remains confidential, the companies included:

- Five large-scale tidal energy technology developers.
- Three large-scale wave energy technology developers.
- Five small-scale tidal energy technology developers.
- Two small-scale wave energy technology developers.
- One utility company.
- One project developer.
- Three supply chain companies.

Initial results from the stakeholder engagement consultation process were presented at a workshop during the All Energy conference in Aberdeen, during May 2013, with over 70 ocean energy delegates in attendance.

2.6.1 Industry Stakeholder Engagement Methodology

The ocean energy industry stakeholder engagement process used semi-structured interview techniques in order to collect responses on several key themes, whilst also allowing the freedom for participants to direct the discussion towards areas that were most pertinent to the development of their own technology.

The 25 questions presented in an industry consultation questionnaire considered the technology development trajectory, collection of performance data, ability to install and retrieve technology, maintenance and reliability, the supply chain, indicative costs and cost reduction opportunities, project pipeline, legislation and regulation. The questionnaire was used as a formula for a semi-structured interview process, an approach that asked the same core questions of each stakeholder, but also allowed opportunity for each interview participant to focus on themes or topics that were most pertinent to their view of product or sector development.

While a structured interview has a rigorous set of questions that can be entirely consistent from one interview to the next, it does not allow one to divert from the pre-determined questions and was deemed to be inflexible in accommodating the views and opinions of a large range of stakeholders, approaching similar challenges from perhaps many different perspectives. On the other hand, a semi-structured interview is a more open technique, facilitating the emergence of new ideas and themes that can be further discussed during the interview process, possibly even directly as a result of what the interviewee has discussed in response to previous questions. Therefore, during the course of each interview, candidates were allowed to elaborate on any specific topic that they wished, and provide additional discussion beyond the topics identified within the initial questionnaire.

The record of the interview process was a transcript, a document containing qualitative data, outlining the points that were discussed during the course of the interview. An inductive coding process was then used to generate quantitative results from qualitative interview transcripts. The references to individual technology developers, supply chain companies, or utilities was removed from the transcript in order to maintain anonymity in the consultation process.

2.6.2 Technology and Project Developer Interviews

The primary form of data collection was achieved through interview with specific wave and tidal energy technology technology developers, supply chain companies with an interest in establishing themselves within the ocean energy sector, and utility companies or project developers with ocean energy projects in their deployment pipeline. The interviews covered a wide range of technology types leading in deployment of pre-commercial demonstration technology (within both wave and tidal energy technologies), and represented a broad range of countries and Technology Readiness Levels (TRLs). By ensuring that both early-stage and mature technology developers were involved in the engagement process, the barriers facing the wider ocean energy sector could be more accurately defined.

As a result of the wide-ranging TRL representation within technology developers, a breadth of responses addressing barriers at all stages of technology development were collected. It is important to recognise the need for research and innovation, even when more mature technology options exist. Therefore technologies at earlier stages of technology readiness played an important role in this data collection, alongside those developers at a mature stage of full-scale pre-commercial deployment.

2.6.3 Analysing the Data

The transcripts detailed each statement and response by the interview candidate. It must be made clear that the output of the interview process (the transcript) alone does not provide the user with any results. Interviews are a qualitative research method, and as a result produce qualitative outputs. To provide results that are of value, in terms of data analysis and detecting underlying themes, the qualitative data must be converted into quantitative form. Qualitative data will allow graphical display of results, and therefore are attractive for providing recommendations, and also provide an appropriate format that will allow the reader to make informed decisions more readily.

There exist a number of possible strategies for conversion from qualitative to quantitative data, and there are two underpinning methods of qualitative analysis – inductive and deductive.

Deductive analysis takes place when a theory is generated and then tested based upon available data. This method is often described as a top down approach, as the initial theory can be subdivided into a number of more specific hypotheses – each of which can be tested using the initial data.

Inductive analysis is a bottom up approach. The hypotheses is generated through observation of the underpinning data, eventually leading to the establishment of a governing theory. An inductive approach seeks to analyse data in a case where no predetermined theory or framework exists. Thus the actual data itself will be used to derive the overarching structures and themes of the analysis. The approach is by nature comprehensive and time-consuming, and is deemed appropriate when unknown themes influence the outcome of the study.

The specific objectives of the stakeholder analysis was to infer dominant themes from the industry, rather than creating a theory and assessing whether the data fits with our hypothesis. This therefore rules out deductive methods. Inductive qualitative analysis allows key themes to come directly from the data, and so an inductive approach was utilised.

There are several different types of inductive method, each with distinctive characteristics that will define the suitability for their use in this work:

- Discourse Analysis: An inductive method which focuses on the language of the qualitative data in terms of the rhetoric and arguments, and the structures in which they are presented. More specifically, this method of analysis targets the language, in talk or text, which can allow an interpretation of multiple meanings within the source material.

Discourse Analysis is concerned with the patterns of language throughout text, and the social and cultural contexts in which it is used (Thomas, 2006). The analysis of language is particularly specialised and not the desired focus or objective of this study. Discourse analysis was not considered to be appropriate for this work.

- Phenomenology: The study of an individual or group's experience concerning particular events. The principal objective of phenomenology is to create a documented account of experiential circumstances through interpreting the events, feelings, and experiences of an individual or group into words (Smith, 2013). While perspective and opinion was necessary for this work, the documenting of feelings and experience was not the primary objective. For this reason, Phenomenology was ruled out.
- Grounded Theory: The analysis process seeks to reveal or generate theory using prominent themes from within the text. A theory is derived to portray the view 'grounded' in the participant (Thomas, 2006). An iterative process allows emerging categories to be refined through multiple readings of the data. It was decided that Grounded Theory, although perhaps a suitable method for analysis of the interview transcripts, put much emphasis on the development of an overarching theory. In the case of the data being analysed within this work, there was likely to be multiple causes and contributions to the challenges faced by the ocean energy sector. While a dominant theory may perhaps emerge, the objective of this work was to outline the dominant themes, without attempting to bring each under a common theory.
- General Inductive Approach: Although broadly similar in many ways to Grounded Theory, the General Inductive approach seeks to allow a user to infer the dominant themes or topics found within a given set of data, allowing the user to draw reliable conclusions from qualitative input data (Jeffrey *et al.*, 2007). This process also limits the outputs to identification and discussion of the most important emerging themes from the data.

'Inductive coding' following a General Inductive Approach was considered as the most appropriate method, and was therefore the chosen process used in the data analysis within this study. While the detailed process of inductive coding will not be discussed herein, further details on the process can be found in the literature (Fereday and Muir-Cochrane, 2006; Thomas, 2006). The inductive coding process utilised software called 'Dedoose' to help enhance the productivity of the coding, given the large quantities of data present in the analysis.

The inductive coding process yielded results on the dominant themes or topics discussed within the interview process by applying specific tags, or 'codes', that could be further investigated to interpret significant industry and stakeholder challenges or trends.

2.6.4 Analysis

The process of inductive coding systematically breaks the available data from its raw format (the transcript), into manageable segments known as excerpts – in this case each individual phrase within a transcript was considered an excerpt. Further reading of excerpts allows for a definition of the theme or topic presented within the phrase. Within inductive coding procedures, repeating the process to remove redundancy or cross-labelling of codes will result in the generation of a model that encompasses only the most important categories.

Inductive coding techniques generally result in the emergence of between three and eight dominant categories (Thomas, 2006). The typed transcripts of each interview were analysed, and specific comments, phrases or statements within each transcript (which, in the inductive coding process, are known as 'excerpts') were assigned labels, or 'codes'. These codes were user generated topics or themes, providing a tag for each phrase based upon the dominant theme being discussed within each specific excerpt. The frequency of occurrence of each code was recorded and explicit discussion of the interpretation and results were then permitted.

After detailed assessment of each transcript from the ocean energy stakeholder engagement, a total of 744 excerpts were prepared for analysis and coding. Seven dominant themes emerged. These seven themes can be seen within the central pie chart of Figure 2.27. Sub-themes associated with each dominant theme were also considered as this allowed for more detailed description of each excerpt. These sub-themes are shown as individual segments around the outside of the pie chart in Figure 2.27. For greater clarity, the themes and sub-themes have been listed in Table 2.1.

The main themes **(bold)** and associated sub-themes *(italic)* were:

- **Technology Design, Development and Innovation:** *Intellectual Property; Collaboration & Knowledge Sharing; Enabling Technology Requirements; Manufacture & Supply Chain; Components; Operability, Reliability & Survivability; Technical Risk; and Third Party Validation*
- **Installation, Operation & Retrieval:** *Foundations & Moorings; Recovery Methods; Vessels*

- **Infrastructure:** *Grid; Testing Facilities; Ports & Harbours; Other Infrastructure*
- **Policy:** *Government Support; Decision Making; Market Growth*
- **Economic:** *Economic Risk; CAPEX Cost Reduction; OPEX Cost Reduction*
- **Environment:** *Legislation; Environmental Impact; Other Ocean Stakeholders*
- **Tools:** *Modelling Tools; Standards & Protocols*

A broader analysis of the data obtained from the stakeholder engagement process, as outlined in Figure 2.27, was considered in wider research – a comprehensive report evaluating each of the dominant themes, providing evidence from the interview process to justify the importance of each challenge to the wider development of the ocean energy sector, can be found in MacGillivray *et al.* (2013a). The focus of the remainder of this chapter will be placed on three dichotomies that became evident within the analysis of the collected data, and which were considered pertinent to the course of this research. Fundamentally, these dichotomies represent different approaches and methodologies for innovation and – while they remain unresolved – barriers to deployment.

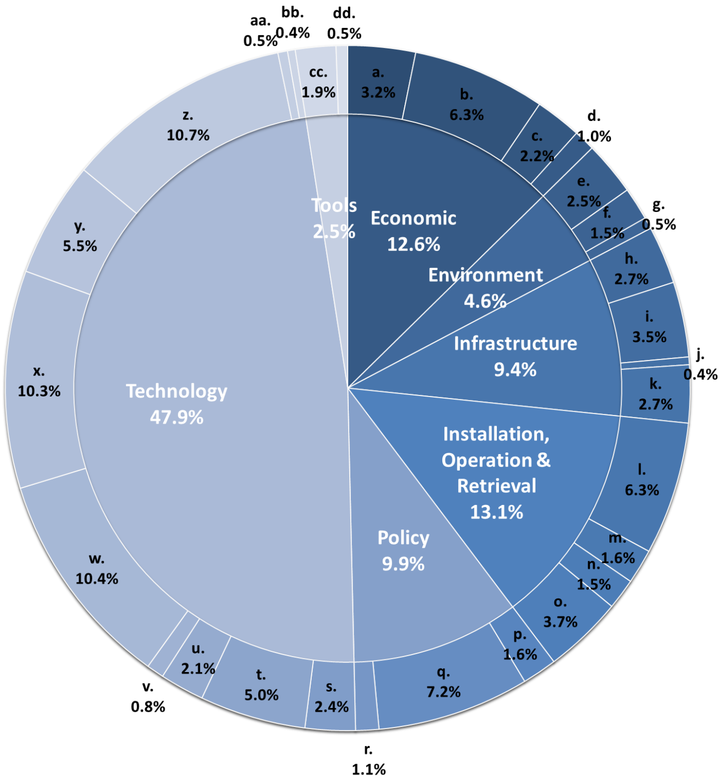

Figure 2.27: Results of inductive coding process

Table 2.1: Key for Figure 2.27

Economic	a.	Economic Risk
	b.	CAPEX Cost Reduction
	c.	Funding
	d.	OPEX Cost Reduction
Environmental	e.	Legislation
	f.	Environmental Impact
	g.	Other Ocean Stakeholders
Infrastructure	h.	Grid
	i.	Other Infrastructure
	j.	Ports & Harbours
	k.	Testing Facilities
	l.	Foundations & Moorings
Installation, Operation and Retrieval	m.	Miscellaneous Installation
	n.	Recovery Methods
	o.	Vessels
Policy	p.	Decision Making
	q.	Government Support
	r.	Market Growth
	s.	Collaboration & Knowledge Sharing
Technology	t.	Components
	u.	Enabling Technology Requirements
	v.	Intellectual Property
	w.	Manufacture & Supply Chain
	x.	Operability, Reliability & Survivability
	y.	Prototype Testing
	z.	Technical Risk
	aa.	Third Party Validation
	bb.	Transportability
Tools	cc.	Modelling Tools
	dd.	Standards and Protocols

Large Scale vs. Small Scale

European and national level market-pull funding mechanisms favour large-scale units, but risk mitigation and lower iteration cost could favour small-scale units. Rapid progression to large scale without fully making use of what can be learned at smaller-scale is prevalent, and there is not a level playing field when it comes to innovation support across technology scales.

The first dichotomy reflected a difference of opinion within the industry, a discussion that still exists despite almost two decades of research and development activity – is large-scale or small-scale technology demonstration and development better for developing the industry? The current development pathway of the ocean energy sector to date has favoured the deployment of MW scale technology – indeed much of the deployment in the UK to date has consisted of large scale technology. The reasons behind this are three-fold: firstly, a certain scale has, to date, been perceived as necessary to generate enough of a return (through revenue from electricity production) to interest potential investors; secondly, MW scale deployments may be needed to initiate increased interest in the market for ocean energy technologies, and, perhaps more crucially, to enable the sector to meet the deployment targets that have been set across EU Member States; thirdly, many of the existing funding support mechanisms have stipulated a need to demonstrate "full-scale" technology – which is generally associated with MW class deployment.

However, there is currently evidence of technology development within the small-scale and community-scale projects, which have the ability to test technology at a lower overall cost and risk than large MW-scale deployments. The first commercial sales of tidal turbine technology occurred within the 50-100kW turbine range.

> "Some [technology developers] compare marine energy to solar panels – many small panels or devices can be combined to make a larger power output; others compare marine energy to modern wind turbines – large machines utilised to give a greater power output per device."

The attractiveness towards pursuit of a particular scale depends on the technology developer and utility involved, with utility companies favouring large scale electricity production from large machines. Some developers are in agreement with this approach:

> "The more efficient, bigger 1MW machine has been tested at EMEC and forms

> the basis for future planned arrays."

Justification for increasing the scale of technology is often attributed to the energy-extraction performance improvements offered.

> "Moving from our first generation technology to our second generation technology created a device that was circa. 50% larger, but had a power output c. 250% greater."

These demonstrate that certain developers focus on larger scale technology as it offers greater efficiency, and higher levels of power capture for modest levels of scale increase.

However, technology development was recognised as only part of a wider web of related needs. Financial justification for smaller scale technology development was demonstrated:

> "While in certain other deployments there is a drive for scale, we have compromised with a smaller unit. A smaller hydrodynamic surface and a smaller foundation will result in a lower cost – although a lower yield. In the current financial circumstances, the smaller unit cost is a more attractive option."

> "Our strategy is to start small and then upscale to big offshore tidal turbines. Smaller turbines are much easier and cheaper to install in the starting phase of the tidal market. Commercialising these 'scaled' turbines will generate a track record and income, and will enable us to develop bigger offshore turbines."

The questions over technology scale within research development and innovation is a significant factor within risk – both technological and economical. A large portion of the difficulties faced by device developers in reaching the next level of technology readiness relate to the high inherent risks of unproven machinery, which, in addition, also has implications in obtaining the necessary financial requirements for the next phase of technology development. One potential pathway for risk mitigation involves development, demonstration and deployment of small technology, with subsequent up-scaling of the technology taking place in tandem with increasing confidence in the reliability and performance of the technology – as was the case for wind turbine technology development. This method could allow a larger number of iterations for a lower overall cost than deploying MW-scale technology from the outset, as a gradual evolution approach can allow a phasing of risk into more manageable financial and technical challenges.

> "Prove technology first [at smaller scale] then innovate. It is very difficult to innovate at large scale as there are considerably greater costs. Devices should follow a gradual evolution approach."

The impact of learning through failure, while not widely discussed, did provide an interesting reflection on the cost of the learning process:

> "One of the best ways for the industry to learn is by putting things in the water and learning from that. Engineers tend to learn from breaking things. Other industries have used this to great effect. Ocean energy needs deployment experience in order to succeed – but putting a £1 million [small-scale] device into the water and breaking that is far less catastrophic than putting a £10 million [large-scale] device in the water and breaking that..."

The impact on technological development from external factors such as funding demonstrated the lack of a level playing field – the eligibility for many funding opportunities was conditional on technology being able to meet strict power output and array size criteria, which were not in line with the more modest scaled development pathway followed by certain developers:

> "the device and projects are not multi-MW arrays, and so funding mechanisms such as MEAD and NER300 require acceptance criteria that our technology cannot meet."

This concern was widely iterated by all companies developing technologies at smaller scale. Certain funding mechanisms have been stimulating the development of large-scale technology. Beyond the technology developers, some consultancies exhibited some concerns over the rapidity of technological up-scaling:

> "Device developers are often moving on too quickly from smaller scale testing. Once they have ticked off one box, they decide to progress, but there is much more that can be done at small-scale than is currently carried out."

Lessons that could be learned at smaller scale, and therefore lower cost, are being overlooked. The ambition of the ocean energy sector with regards to accelerated innovation is pressing developers towards large scale technology, perhaps inappropriately.

> "The industry has been too ambitious too soon."

However, as with many of the challenges that are technological in nature, policy and economic factors also play a role in some of the development and innovation decisions.

> "There is pressure from investors to deploy at sea, which can result in premature technology deployment."

Design Commonality vs. Novelty Through Innovation

Using off-the-shelf components to keep costs low, whilst exhibiting recognition of a need for new components and step-change cost reductions to improve overall life-cycle performance of technology.

The second dichotomy reflected the challenge of achieving step change performance improvements or cost reductions through novel sub-systems or components, whilst enabling a supply chain market opportunity through commonality between systems. In some instances, technologies may look favourably at novel components, sub-systems, or systems, but this comes with added difficulty in obtaining performance guarantees.

> "You cannot get a warranty for a bespoke piece of equipment"

There is a trade-off between using novel components that may offer technical simplification, and using off the shelf components where operation in relevant environment is already proven – and where it is possible that warranties may be provided. Investment and investor relationships are often built around perception of risk. The relationships also develop around the reliability of components and technology. Technology developers are unable, at present, to offer production guarantees, but project developers require a certain level of baseline guarantee that can help with the investment case and aid the decision on which technology to deploy at a given site, as is conventional practice within the wind energy sector.

> “Investors are looking to tried and proven technology. There is not enough return on new technologies, and new technologies also pose a high risk!”

Weaknesses in existing systems will be identified during the pre-commercial demonstration phase of new technology, and it is almost certain that optimisation of existing technology is not yet complete. Novel components may be necessary.

> “new components will be needed in order to improve the life cycle performance [of wave and tidal energy converters].”

However, there was significant agreement that off-the-shelf components were of importance in the design of current generation systems.

> “The only novel part of turbine is the blades. All other components are off the shelf, marinised components. It is evolution rather than revolution.”

> “[We are] designing the turbine based around what is currently available, not attempting to design a bespoke device. The supply chain will follow with new products if they see a market opportunity and a reliable order stream.”

> “[We] use power industry and wind components already proved in many hours of operation, but these must be marinised and adapted for 5-year life. This development and testing is done by component suppliers”

> “Standardised ‘off-the-shelf’ components are used as far as possible”

There is widespread recognition within the wave and tidal energy sectors that there is an opportunity for improved design commonality in components and sub-systems. There is, however, a lack of agreement on how this can be achieved in practice. Most developers agreed that design consensus within certain systems or sub-systems would bring benefit to the development of the sector and supply chain, but there is not a great level of agreement over the specific details behind design consensus. Project developers had an interesting perspective on the issue, alluding to the need to compromises to be made:

> “Compromises on design and/or cost may have to be made when achieving commonality in design for a particular component such as foundations, or nacelle

> quick connection. A step change in thought is required to achieve this aim, as well as buy in from multiple device developers"

Without any significant evidence of collaboration between developers at present, the 'pseudo design commonality' is perhaps a reflection of developers' progression of their own technology towards mass manufacture, rather than an attempt to try and reach greater levels of design consensus amongst the wider sector. Increased cross-sector collaboration would certainly be of benefit to the overall rate of deployment, and greater levels of transparency would enhance the development of both the wave and tidal energy sectors. Without overcoming this barrier, device development will follow a more costly and lengthier development process than is desired by local and national governments, and industry stakeholders.

The wave and tidal energy sector suffers technological fragmentation, with many stakeholders working on individual in-house developed solutions for a wide range of activities along the supply chain. With every new design and technology there is a significant engineering requirement in Non-Recurring Engineering (NRE). NRE, design work, is a one-time technical effort made for the innovative design and development of a new product or service. The cost of design for a new product will inherently result in high costs compared to a product that is the result of standardisation.

Within product development, design costs will occur at the beginning of the project and product lifecycle. Once completed, the design should not require significant further engineering work, and so the cost of future products to the same design will be lower than the cost of the initial product. Within wave and tidal energy, there has been continued requirement for NRE within device designs. Despite the high costs associated with initial pre-commercial demonstration units, there is a significant level of NRE effort associated with each design iteration.

There is a need for greater levels of commonality in order to reduce the cost of energy, and allow for a greater market potential if a new product solution was to be developed. There are certain areas that could utilise commonality across a range of technology developers, such as foundation or mooring design, or design of device quick connections and latching systems. Reducing the level of NRE needed for ocean energy systems will help to significantly reduce the overall cost of the product. This needs the buy in from multiple technology and project developers, and component suppliers – it will not work without collaborative effort.

Intellectual Property (IP) Protectionism vs. Data Sharing

IP can be seen as a useful bargaining chip or a barrier that is crippling innovation. Lack of knowledge transfer within the sector is causing duplication of work, and preventing diffusion of knowledge.

In order to facilitate greater levels of knowledge transfer, there needs to be an agreement as to what data should be shared by developers. Certain information would be more readily transferable without invading IP rights, such as ecology and environmental data, or foundation and mooring solutions.

On the whole, there is agreement within the sector that collaboration is desirable, but there needs to be progression from 'talking about collaboration' to actually carrying out collaborative projects. The biggest barrier to collaboration is IP and arguments over ownership of generated IP – the third dichotomy. While the nature of IP needs to be respected, barriers that slow or hinder the progression of the ocean energy sector are undesirable. At present there is an over-protective attitude towards IP, one which causes a breakdown in collaboration. The focus should not be on generating IP for personal gain, but more compromise on producing solutions that benefit the sector as a whole.

There will, of course, be strategic areas in which developers are not willing to collaborate, as private investors will generally insist on some IP protection in order to protect their investment and prevent anyone from copying their idea, however, these need to be considered carefully so that they do not hinder the overall development of the sector.

> "There shouldn't be complaints and arguments about IP and design details. The entire ocean energy sector is a big R&D project. No developer has a market share, and no one has made commercial sale of several devices. This attitude and mindset needs to change, as there is no need for this attitude before there is even a commercial product that can acquire some share of a market."

The role of Intellectual Property (IP) has been the source behind the attitude of secrecy, and the lack of transparency and knowledge sharing within both the wave and tidal sectors. There are two significant attitudes to IP found within the analysis. The first sees IP as the 'bargaining chip' for small companies to enter into dialogue with the rest of the sector.

> "Device developers are small scale companies. IP power is very important to small

> companies, so they are reluctant to give up IP."

Whilst it is recognised that there is an important need for companies to develop their skills, the nascent stage of the industry means that much learning needs to take place before best practice can be fully developed. Greater levels of knowledge sharing would accelerate sector development, and the lack of efficient knowledge transfer can be considered a significant barrier to accelerated deployment of ocean energy technologies. The lack of knowledge sharing currently results in much duplication of effort between different organisations and technology developers. Funding is being spread thinly across a range of different technologies, and the funding challenge faced by developers can lead to the demise of particular technologies – with the risk of losing the learning that has taken place within the deployment experience gained. However much shared learning could be taking place if funding was dedicated towards specific sub-components with cross-transferable application in a number of technologies. The over-reliance on IP was presented as a major hurdle that was presenting a barrier to deployment. This was the second attitude towards IP, particularly emphasised by a number of supply-chain stakeholders.

> "There is an over-reliance on the value of IP in the industry, especially given that no one has long term deployment experience or generated profit from their device."

This is a poignant fact, particularly given that failure to overcome IP issues could result in stagnation of sector development, or at least the contribute to extended lead-times (and costs) for project deployment. The real winners in IP are unlikely to be technology developers.

> "IP makes lawyers rich, it doesn't necessarily make device developers rich."

Collaboration and knowledge sharing was recognised to be of significant importance and the responses to this theme were in general agreement – there is a greater need for enhanced collaboration and knowledge sharing within the sector, in principle, than currently exists. However, in practice, the way in which greater collaboration could be achieved was not easy to define, and an attitude of secrecy prevails. While many were in favour of seeing increased collaboration and knowledge sharing, there was still a reluctance to share existing learning. Several factors contributed to this impediment, one of which includes pressure from external sources such as investors.

> "[Sometimes it is] difficult to establish relationships due to the investor stance and pressure from investors not to share knowledge or sensitive information."

Some developers were very particular about the importance of keeping the information 'in house', and therefore limitations in the practical willingness of knowledge sharing were evident within the data.

A particularly positive example of knowledge sharing came from developers based in Denmark with access to funding through Energinet (The national transmission system operator in Denmark). The recipients of funding through Energinet are obligated to provide certain performance and operational data as a condition of funding. This set up is different to the conditions of funding in other European Member States, and provides a more transparent mode of operation for emerging technology development. Given the high capital costs of existing technology, and limited opportunity for financial return at this stage, transparency can help to provide investor confidence in technology performance. This could be an apt requirement for all future funding mechanisms, and one which could radically alter the level of knowledge sharing that takes place across the industry.

To date, there has been very little transparency from developers with regards to specific reliability and failure information, or sharing of knowledge component reliability between different developers. Energinet funding requires that, over the course of a two-year period, all stops, alarms, and maintenance of machine be documented and the information made available publicly. This requirement will allow the creation of an open access log of system faults, and identification of any weaknesses within the system as a whole. By allowing this level of transparency, failure data no longer becomes part of a 'black box' system, and confidence can be gained in technologies as tangible improvements in performance are made.

2.6.5 Stakeholder Engagement Conclusions

Direct engagement with the ocean energy sector has revealed the challenging conditions that technology developers and project developers are operating within. For those developing the technologies, there is significant pressure for fast deployment in short timescales, both from an economic and a political level. Financial pressures exist through the requirement to provide immediate returns for investors. Political pressures arise from competition with other renewable energy technologies that may offer a more competitive and attractive cost of energy for policymakers, and the general lack of consistent and long-term policy clarity in a number of potential markets where strong resource exists. Optimistic deployment forecasts, which have pushed the sector to achieve large-scale deployments in the short-term, are misaligned with the necessary development steps required by the ocean energy sector, and indeed the type, and level, of funding available. Many of the sub-themes extracted from the inductive coding process reflect this conflict. There is further misalignment between the scale of ambition within the sector and the level of technological readiness. In addition, technological pressures exist in that demonstration of reliable, operable, and affordable technology must still take place – no technology under development has yet proven to fulfill each of these criteria in a manner in which investors can continue to confidently support large-scale array deployment.

Using direct engagement with the ocean energy sector as the source of information, the industry stakeholder engagement confirmed that there is still significant uncertainty across a range of themes and topics. However, technological, economic, and political themes present a majority of the industry challenges, gaps in knowledge and barriers to deployment. The remaining sector uncertainty and existence of a number of fundamental questions surrounding technological development, economic risk and policy clarity suggests that an accelerated push for large scale deployment is perhaps premature in the wave and tidal energy sectors; numerous technological, economic, and political issues must be considered and resolved prior to the realisation of commercially sustainable wave and tidal energy.

Some of the unanswered questions that still linger over the nascent wave and tidal energy sectors can be summarised as follows:

1. From a technological development perspective, the question over appropriate technology scale (small-scale vs large scale) still splits the opinion of technology developers and industry stakeholders alike. There is a need to provide an answer or solution to this

dichotomy in order to provide the most appropriate technology development support to this nascent industry. The innovation process requires iteration, but innovating at large scale involves large cost – costs that are causing a stumbling block to further unit deployment. An appropriate scale for cost-effective technology iteration has not been settled upon within the industry.

2. Most wave and tidal energy technology developers state they are using off the shelf components within their design, however much design diversity still exists across the sector. A pseudo design-commonality is perhaps prevalent, whereby the commonality exists for individual developers looking to secure device design that is suitable for batch and large scale manufacturing. Commonality between different manufacturers or developers of technology is limited, other than perhaps certain fundamental design principles, particularly within tidal stream energy converters. Much work is needed to establish commonality in core elements of projects. Furthermore, transparency (from all industry stakeholders, disseminating successes and failures, lessons learned, what has been achieved and what remains to be resolved) and clarity (on the expectation requirements for knowledge sharing, particularly where public funding has been sourced to enable a given technology development or deployment) could bring much benefit to the nascent stages of wave and tidal energy technology development. The over-reliance on IP, in conjunction with knowledge protectionism at the early stage of technology development, is limiting knowledge transfer across the sector.

3. From an economic perspective, affordable iteration is an area that requires greater attention. The current large-scale MW dominated deployment trajectory has resulted in unit iteration costs that appear to be beyond the level of investor willingness. Many of the economic arguments made by project developers suggest a need to rapidly ramp up to large arrays or large-scale technology in order to make projects commercially attractive. However, investment support has not rallied around this technological development step.

4. It has become clear that many wave and tidal energy projects under development are in a position where they are not considered bankable under current economic and political conditions. From a policy perspective, this could suggest a number of possible contributing factors: *(i)* The wrong projects or technologies may be entering the development/deployment process, ones that are too expensive, have high uncertainties, and are taking a significant leap into the unknown from limited evidence through experience from single unit demonstration; *(ii)* policies and support mechanisms are entirely mis-

aligned with the technology development process, stimulating the development of the wrong technologies at the wrong scale; *(iii)* the industry is trying to build out multiples, when a commercially viable single device does not yet exist; there is a push for going big before small devices have been fully developed and proven;

5. There is a recognised need for the ocean energy sector to trial wave and tidal energy technology under representative operating conditions. However, the financial cost of doing so under the current research, development and innovation environment is presenting a significant barrier to deployment. Economically sustainable development of technology is under question, and in order to achieve the vision of commercial wave and tidal energy technology a different approach may be needed from the current development research, development and innovation environment;

6. The technological step being made by many device developers is greater than the financial will or ability of the private sector investment community at this stage in technology development. The magnitude of the financial requirement in order to deploy large-scale technology (which may still be largely unproven in terms of long-term reliability) is creating a funding 'valley of death', which developers must successfully circumnavigate – leading to very lengthy timescales between individual unit iterations. Many challenges still remain, and dichotomies create rifts between stakeholders within both technology development and the wider supply chain. This research, development and innovation environment is not conducive to developing economically sustainable wave or tidal energy technology. The ocean energy industry still faces many technological, economic, and political challenges on the pathway to commercialisation, in spite of significant expenditure to date. The misalignment between technology iteration costs and private sector investor willingness needs to be rectified if significant progress is to be made towards securing a viable ocean energy sector capable of providing a long-term contribution to the global energy mix.

2.7 Framing the Direction of the Research

The technology and sector review, and the ocean energy stakeholder engagement have established the extent of technological development that has taken place within both the wave and tidal energy sector, yet clearly demonstrate that many challenges still remain. Technology commercialisation is not likely to be imminent. Although a significant wave and tidal energy resource exists, the challenges must be overcome in a technologically robust and economically sustainable manner if there is to be a long-term future for wave and tidal stream energy. The evidence within this chapter has defined the need for, and framed the direction of the research carried out within this thesis – the need for economically sustainable formative development of wave and tidal stream technologies.

Chapter 3

Literature Survey

3.1 Chapter Introduction

The Oxford English Dictionary defines innovation as follows:

> "**Innovation (noun):** A new method, idea, product, etc." (Simpson *et al.*, 2002)

However, innovation is about much more than just a new method, idea, or product. Business-Dictionary.com provides a more eloquent definition of innovation:

> "The process of translating an idea or invention into a good or service that creates value or for which customers will pay." (BusinessDictionary.com, 2015)

This improved definition implies that in order to be recognised as an innovation, a method, idea or product must be replicable – creating a good or service that has application beyond a single prototype; it must be economic – available at a cost that customers are willing to pay; it must satisfy a specific market or user defined need.

Ocean energy could be considered to be on the cusp of commercialisation and array deployment, yet it has been at this stage for some time. Chapter 2 identified and outlined some of the significant gaps in knowledge and barriers to deployment that are causing challenges for sector progression. These identified challenges are consistent with technology in the nascent stages of development, and not those on the cusp of commercialisation and diffusion. The innovation and technology trajectory for wave and tidal energy has not yet provided answers for the questions that are being asked, or addressed the technology challenges.

Innovation is often referenced within much of the leading academic and industrial ocean energy literature as a means of unlocking future cost reduction (MacGillivray *et al.*, 2013a; O Rourke *et al.*, 2010; SI Ocean, 2013; Carbon Trust, 2011; Low Carbon Innovation Coordination Group, 2012; Energy Technologies Institute, 2014), yet there is very little published literature specific to ocean energy that defines how tangible innovation is manifest, and what affordable innovation pathways could, or indeed should look like.

The process of innovation has been the subject of research within fields of engineering, policy, economics and social science, making it a multi-disciplinary topic with a number of useful applications. It is necessary to gain an understanding of the academic science that can be used to enhance our understanding of various characteristics of a research, development and innovation environment, and how the progress of innovation can be benchmarked using innovation theory techniques. The application of this understanding to the wave and tidal energy sector will assist in the search for appropriate techniques that can analyse and positively influence the development pathway of ocean energy technologies, therefore providing suitable evidence to support any necessary transitional changes.

The aim of this chapter is then to provide adequate introduction to the use of established innovation theory, and the justification as to whether certain defined approaches can be used in a novel way in order to identify, with assurance, whether the ocean energy sector's current research, development and innovation environment, represents an economically sustainable and technologically sound trajectory, furthering academic knowledge in this field of research.

3.2 Innovation Theory Introduction

The roots of innovation studies lie early in the 20$^{\text{th}}$ century. The studies of French sociologist Gabriel Tarde fundamentally describe the essence of communication between individuals as "the influence of one brain upon another brain" (Tosti, 1897). This influence implies, as a necessary condition, the formation of two separate classes, a *model*, and a *copy*. The model is the first-of-a-kind invention or the improvement (no matter how small) of an existing social phenomenon; a copy is the imitation which allows the development, replication, progress and expansion of this model across a wider social representation (Tosti, 1897). The subsequent differing rates of diffusion of inventions and discoveries played a central role in the thinking of Gabriel Tarde who, while investigating the more personal aspects of social intercourse and the social milieu, made early progress in what could be considered as a theory of innovation and diffusion.

Modern interpretation of the term innovation is often accredited to Schumpeter, who found innovation is a cyclical (iterative) process, defined as "Krieslauf" (translated as circular flow), rather than being made of equally placed events throughout time (Schumpeter, 1983). Innovation was perceived by Schumpeter as the driving force behind economic growth, with innovation being defined broadly as "the commercial or industrial application of something new" (Schumpeter, 1983).

Innovation encompasses a wide range of activities, which can also include the search for solutions to a problem, the realisation of new products processes or techniques through research and development, or adaptation of existing products, processes or services in order to enhance the performance of a given process or system (Utterback, 1975a; Dosi, 1982). The discontinuous fluctuation of innovation is linked to finance and investment in new opportunities – which, if successful lead to the copy or imitation, or indeed secondary innovation of supporting technology or service – creating a period of economic growth. As innovations reach market and competition sets in, the effect of cost reduction for the consumer results in a reduction in profit margin for the businesses offering the product or service. The implications of this reduced profit margin, in addition to the potential challenges and pitfalls of rising costs, can lead to the stagnation or contraction in growth of a company, an industry or sector, or of an entire economy. In the latter, a resulting recession would therefore require a new innovation process to take place in order to drive economic growth once again (Schumpeter, 1983).

In Schumpeter's theory of economic development, the stages of development, in which innovation is fundamental, can be classified into five types (Schumpeter, 1983):

1. Establishing a new product – in which consumers have no experience, or an improved iteration (cyclical process leading to improvement) of an existing product;
2. Utilising new forms of manufacturing, production or distribution, not yet established in the sector;
3. The creation of a new market segment or revenue stream;
4. The acquisition of novel sources of raw materials, feedstocks, or intermediate materials;
5. A novel structuring of corporate organisational processes.

Furthermore, the development of a specific stage will often exhibit a structured progression as it moves from ground breaking findings through to wider adoption within the sector in which it is placed. This progression was separated into three distinct themes by Schumpeter: invention, innovation, and diffusion (Burton-Jones, 1999). The theory of innovation, due largely to the early influence of Schumpeter, draws a distinct line between invention and innovation. The seed of an idea, the initial inspiration and scientific discovery is not the cause of economic growth. In order to realise the economic benefits, the invention must be made ready for a market (innovation), and then through a process of diffusion enter into widespread adoption, which is generally then followed by imitation from other actors entering the market. The ideas created by scientific discovery require additional effort in order to see wider implementation. Innovation should then only be considered to have reached successful completion upon the first commercial application of a technology, process, or system (Freeman and Soete, 1997; Grubler *et al.*, 1999).

3.3 Innovation System Evolution

Innovation is explicitly investigated and the many associated characteristics assessed in the literature (Vantoch-Wood, 2012a; Freeman and Soete, 1997) and research has demonstrated that models of innovation systems have developed and evolved over time. The part-time nature of innovators in the eighteenth and nineteenth centuries has been largely displaced by R&D work taking place in research laboratories in academic and industrial institutions worldwide in the twenty-first century. The 'professionalisation' of scientific advances and technology development has been shown to associate with three underpinning changes (Freeman and Soete, 1997):

1. An increasing trend in the scientific complexity of technology;
2. The progress from bespoke unit and small batch production to mass production (and the associated growth in complexity of processes and manufacturing equipment), and the need for R&D activity to take place in specialist research facilities separately to the rolling production lines;
3. The 'division of labour' (as investigated by Adam Smith) provided significant advantage to specialist staff and facilities.

An increasingly challenging problem faces the arena of modern policy: how to manage appropriate incentive mechanisms to monitor and control the direction of technological change, while accelerating the rate and enhancing the impact of technological (and economic) progress (Freeman and Soete, 1997). The dynamic changes to the innovation system over the latter half of the twentieth century has been well summarised in the literature, where five generations of innovation system were outlined (Rothwell, 1994).

The first generation innovation process follows a 20 year post Second World War period, where rapid growth took place within the industrial sector and new industries formed as a result of technological invention. Revitalisation of existing sectors took place, together with improvements in performance and efficiency in production. Demand outstripped production in many cases during the earlier parts of this stage. Society in general valued science and technology for the contribution it made in enhancing quality of life. These societal values were reflected by the policy makers, who ensured that stimulus of scientific discovery and application (across both academic and industrial research institutes) was supported through funding allocated to R&D programmes. The innovation process was assumed to be linear, as scientific discovery was assumed to be followed by technology development, and eventual diffusion. This era can be considered to have a 'technology push' focus, where stimulating innovation at the stage of scientific discovery would result in greater economic successes for companies through developments of increasing numbers of commercial products.

During the second generation innovation process of the mid-1960s to early 1970s, the technological advances made were predominantly based on iteration of existing technologies. As new players entered into existing markets, increasing levels of competition were seen – with a focus on product marketing driving the innovation and market share of given companies and products. This model of innovation can be classified as 'demand-pull' (or 'market-pull') as the innovation was seen to be driven by market need/demand, and R&D focus was shifted from scientific discovery to meeting the perceived needs of the market. However, the innovation process was still assumed to be linear.

Throughout the 1970s and into the early 1980s, the innovation process shifted again for a third generation of innovation process. Focus leaned towards a combination of technology-push and market/demand-pull directed innovation. A large increase in the level of research activity investigating the innovation process itself and its impact across a number of industries and countries began to take place (Utterback, 1975b; Szakasitz, 1975; Rothwell, 1994). At this time, feedback loops within the technology-push and market/demand-pull innovation drivers began to show divergence from a purely linear innovation process, with a focus on technological capability and how improvements in technology could satisfy a perceived need in the market.

During the fourth generation innovation process, between the early 1980s and early 1990s, greater levels of collaboration between organisations emerged – prompting a structural shift in the mode of innovation. No longer was innovation perceived to be a linear process; synchronous innovation activity across a number of departments or organisations (whether through early engagement with supply chain companies, or through engaging multiple in-house design teams) occurred, necessitating a need for improved information exchange.

The fifth generation innovation process, initiating in the mid-1990s and ongoing, must use superior product development strategies that ensure greater consideration of latter processes at an early stage of design (for example, design for manufacture), therefore increasing efficiencies in design, manufacture, and eventual end use. Flexibility of products, manufacturing, and organisational structures are deemed to be essential to unlocking high rates of technological change, with short product turn around times. A focus on lean manufacture and reduction of process waste emerged. The focus of products will generally consider operability and reliability as core performance features. In a fast-changing world, the ability to innovate rapidly can define the competitiveness of a company in a given market. An example of this type of innovation can be seen in the automotive industry, with Volkswagen group's move to modular chassis platforms (the MQB platform) allowing a range of vehicle sizes to be produced from modular components, therefore cutting costs and reducing the time between concept car and commercial production line (Buiga, 2012).

Policymakers must respond to the changing needs that characterise the direction and pace of innovation and technological change, however this complexity in administering the correct levels of support, with the correct choice of policies, runs the risk of leading to negative impact on the specific innovation under consideration if incorrect policies are administered (Nemet, 2009).

Within the context of this thesis, it is recognised that there are many technological, economic, political and sociological aspects of innovation that are widely covered within the literature. However this work is focusing only on the aspects of innovation theory that are directly applicable to techno-economic assessment of the commercialisation of a new technology – in this case within the field of ocean energy – and how these aspects can be linked directly to the success or failures of the research, development and innovation environment at stimulating the emergence of an economically sustainable and commercial ocean energy sector.

The innovation process, and the resulting technical change, can only achieve success if investment in innovation is established and maintained well in advance of a specific technology becoming cost competitive; successful innovation must be achieved before profit and return can be expected (Grubler *et al.*, 1999).

3.4 Technological Change

The term ‘technological change’ can be used when the combination of invention, innovation, diffusion, and imitation of technology results in the progress and development of technology for the benefit and advance of mankind. Product creation, performance and efficiency improvements of existing products, and improvement in process effectiveness are widely recognised to be foundational to economic growth (Grubler *et al.*, 1999) and technological change develops from within the wider economic system (Jacobsson and Bergek, 2004).

3.4.1 Diffusion of Innovation

The theory of diffusion of innovation was widely discussed and developed by E. M. Rogers in 1962, with the publication of ‘Diffusion of Innovations’ (Rogers, 1995). Diffusion is defined as “the process by which an innovation is communicated through certain channels over time” (Rogers, 1995). While focusing on the nature of diffusion of technological innovations, Rogers work refers the reader to early pioneering work by Gabriel Tarde and the act of imitation as diffusion studies that were well ahead of their time. The diffusion of a concept, or indeed failure to diffuse, rests upon a number of conditions ranging from technological through to social. While inventors of a new idea may be optimistic that rapid and widespread innovation and diffusion will result from the understanding and influence of investment by early adopters, adoption and diffusion is frequently a lengthy and challenging process and the diffusion of innovation occurs most frequently at a slower than anticipated rate (Oldenurg and Glanz, 2008). Even scientific advances with a readily observable benefit can be slow to diffuse. Perhaps the worst offender is the adoption of citrus juice in preventing scurvy amongst sailors, with diffusion and adoption taking place after a lag of approximately 264 years from first discovery (Mosteller, 1981).

The most prominent early research in diffusion can be attributed to Ryan and Gross, who investigated the diffusion of a novel hybrid corn seed capable of enhancing crop yields across two Iowan communities (Ryan and Gross, 1943). The study identified that, while important, the early adopters are not the drivers of growth. The fundamental aspects of diffusion resulted from the communication between actors (the farmers interviewed during the work) networks and channels of communication that existed between those who used the new hybrid corn seed, and those who did not. The work of Ryan and Gross can be considered as instrumental in the formation of the classical diffusion paradigm (Rogers, 1995).

Despite the differing technologies or ideas under consideration within the literature surrounding diffusion, the findings have converged upon a dominant theme: diffusion of innovations tend to follow an s-shaped curve when level of adoption is plotted against time. In its simplest form, the s-curve can be approximated using a relatively straightforward, single parameter, logistic function, defined in Equation 3.1.

$$y(t) = b_0 + \frac{1}{1+e^{-b_1 t}} \tag{3.1}$$

where $y(t)$ is the proportion of adopters at time t; b_0 the y-axis intercept; t is time; and b_1 is the diffusion rate parameter (Valente, 2005).

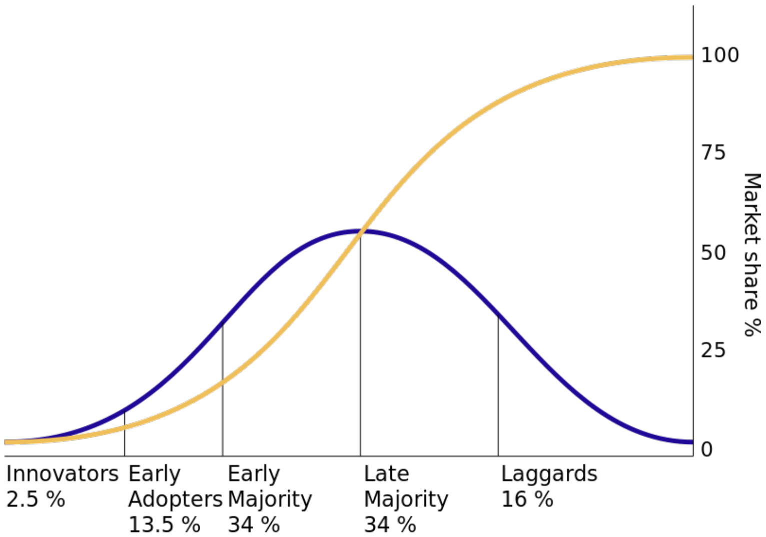

Figure 3.1: The diffusion of innovation (yellow curve) and rate of change of diffusion (blue curve) split by associated stages of adopter (Source: (Rogers, 1995))

The s-curve diffusion of technology can be seen diagramatically in Figure 3.1. Typical values for t can depend entirely on the product or market that the product will serve. For energy sector technology, the timescale of the diffusion process can be several decades. Within the automotive industry, a particular model of vehicle can be produced for several years, with the diffusion process occurring over a span of five to ten years. For modern consumer electronics, such as mobile phones, the diffusion process is significantly shorter, in the order of months.

The S-curve of diffusion outlined in Figure 3.1 can be broken down into three sections. The first section consists of the innovators and early adopters. The second section consists of the early majority and late majority. The third section consists of the laggards. These sections have been defined by Grubler *et al.* (1999) as:

1. Niche markets
2. Pervasive diffusion
3. Saturation

In the example of logistic growth above, the early stages of development, when technology is still considered nascent, is characterised by low overall levels of deployment and slow levels of growth. As adoption of technology begins, the rate of increase in deployment is very gradual. After early adopters, an increase in the rate of deployment is seen. This increased rate of deployment causes a rapid exponential increase in the cumulative levels of deployment, and is sustained for a period of time. Once the market begins to saturate, there is a decrease in the rate of deployment, which results in the leveling of the s-curve profile (Grubler *et al.*, 1999). Further examples of the s-curve can be found in the literature, with examples of societal and technological breakthroughs revealing that the s-curve is applicable to both social change, and technological diffusion (Grubler, 1995; Burton-Jones, 1999). Examples include technological subjects such as the modelling of market penetration of new telecommunications services (Brewley and Fiebig, 1988), and the evolution of infrastructure in the USA – presented as percent of saturation level with respect to year for a number of technologies (Grubler *et al.*, 1999).

Bringing the theme of diffusion into the energy system, the literature exposes the energy system changes over time, with different power generating technologies occupying different shares in the overall generation capacity over time. Indeed, after a period of diffusion, a technology can become obsolete as it is replaced with a newer and more efficient alternative. Logistic substitution functions describing this process are discussed in Marchetti and Nakicenovic (1979), who present the hypothesis that all energy technologies can be considered as competitors within an ever-changing market, and that the pursuit of advancement and innovation can result in the obsolescence of older technologies. Historical experience has demonstrated that the market saturation point of the s-curve can be followed by a downward trend as technologies are replaced by higher performing alternatives (Marchetti and Nakicenovic, 1979; Grubler *et al.*, 1999).

3.4.2 Logistic Growth Functions

Figure 3.1 and the diffusion of innovation can be defined mathematically by use of a logistic growth function. The logistic growth function originated as an extension of the exponential growth function, designed to constrain the maximum upper value of a given function or variable where limitless increase is deemed unrealistic (Tsoularis and Wallace, 2002). This limit, the saturation level, provides a numerical upper bound on the growth of the function. The explanation of population statistics within P. F. Verhulst's *"Notice sur la loi que la populations suit dans son accroissement"* in 1838 (Verhulst, 1838) is widely regarded as the first scientific contribution to the understanding of what is now known as the logistic equation.

The logistic growth model is able to reflect the changes in growth rate for a particular variable over time: The process follows a sigmoidal (s-shaped) profile where the rate of growth initially accelerates (and can be initially almost exponential in nature), before reaching a point of inflection and eventual deceleration in the rate of growth as a maximum limit is approached. A number of logistic growth models have been suggested as useful for modelling the growth of biological populations over time, but the application of these functions extends well beyond the fields of biology or social science (Tsoularis and Wallace, 2002).

Logistic growth functions have been used as a tool to characterise the diffusion of innovation process across a range of processes and technologies. Diffusion of innovation theory emerged during the 1960s – but has since become a popular topic of research within many disciplines, including economics, statistics, marketing, sociology, psychology, and industrial engineering (Rogers, 1995).

Within the energy sector, application of logistic functions are utilised for the forecasting of technological change (Sharif and Islam, 1980), global energy usage change together with the senescence and substitution of older technology for more advanced sources of energy (Marchetti and Nakicenovic, 1979), and for the modelling of energy system growth and technology change based on empirical data (Wilson, 2012; Wilson *et al.*, 2012), where the capacity penetration over time and the time-frames associated with development phases for of a number of energy technologies were considered. Forecasts of energy technology industry growth using logistic growth functions have suggested that a methane dominated energy economy could be in place by 2030 (Smil, 2008).

Existing research has considered application of 3 Parameter Logistic (3PL) models within energy sector technologies. 3PL functions provide curve-fitting through nonlinear regression models that are defined by three parameters: the maximum asymptote of the curve, the inflection point, and the gradient of the curve at the inflection point. The simplicity of the 3PL growth function can yield useful results when it is deemed an appropriate fit. However, it should be noted that there are some limitations to the use of simple 3PL functions, such as the strict enforcement of symmetry about the point of inflection (Brewley and Fiebig, 1988). Additionally, the diffusion process may occur at varying growth rates over the course of the sample (Brewley and Fiebig, 1988), an attribute that 3PL functions are unable to model accurately. 3PL functions assume that growth initiates from a zero value at the outset. Figure 3.1 was an example of a 3PL function.

Adding a fourth parameter, the minimum asymptote, can enable curve fitting where the process or system being modelled initiates from a non-zero value, for example population modeling for a country, modelling of the spreading of a virus or bacteria, or growth in level of observed bacteria from an initial culture. Many examples of 4PL logistic growth functions are considered within the literature, including the Gompertz function and Weibull distributions (Sharif and Islam, 1980; Tsoularis and Wallace, 2002; Banks, 1994). There are limitations and inflexibilities associated with a number of logistic growth functions as a result of specific requirements for points of inflection and degrees of asymmetry (Brewley and Fiebig, 1988; Tsoularis and Wallace, 2002).

A more flexible logistic growth function has been identified, a five parameter logistic (5PL) non-linear regression model that allows for asymmetry about the point of inflection and a non-zero lower asymptote, thus removing the constraints of 3PL and 4PL functions (Richards, 1959). The 5PL growth model is therefore an appropriate tool for representing the development of technology, advancement of state-of-the-art, and diffusion of innovations into commercial application within the energy sector, where non-zero lower asymptotes exist in unit-level deployment, and definitive symmetry about a point of inflection is perhaps plausible, but unlikely.

Logistic growth functions within reference literature on energy technologies consist primarily of three parameter logistic growth functions (Wilson, 2012), with limitations described above. The 5PL model can be represented by Equation 3.2 (Commo and Bot, 2014):

$$y = B + \frac{(T - B)}{[1 + 10^{b(x_{mid} - x)}]^s} \tag{3.2}$$

where x is the x-axis value at the point of interest; y is the parameter value at point x; B is the minimum asymptote; T is the maximum asymptote; b is the Hill slope (curve steepness, $\frac{dy}{dx}$); x_{mid} is the x-coordinate at the inflection point; and s is an asymmetric coefficient.

Each parameter of the function is explained diagrammatically in Figure 3.2, with the parameter s reflecting a shift in the asymmetry of the curve.

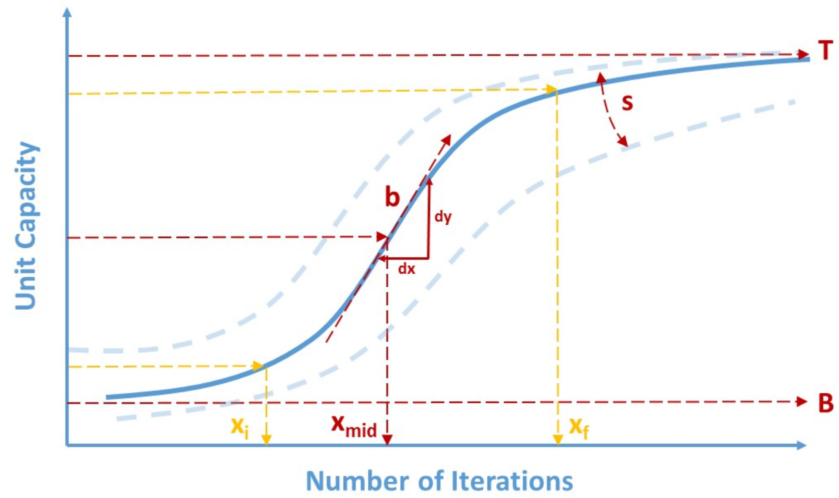

Figure 3.2: Parameters of the 5PL Function explained

3.4.3 Three Phases of Technology Development

As technology enters a market and diffuses towards market maturity, it has been recognised, based on analysis of technology within the energy sector, that three distinct technological processes are evident, as shown in Figure 3.3. These three phases can also be characterised by a logistic growth function, with the y-axis parameter dependent on the technological focus of the study: growth of technology at a unit-level can be demonstrated by assessing increasing unit capacities; and growth of an industry can be demonstrated by assessing increasing cumulative installed capacity.

1. A ‘formative phase’ where deployment of a large number of smaller-scale units, and many iterations, takes place over a period of time. Evolutionary changes in design will take place as a technology is optimised. Only modest increases in unit capacity are seen (Wilson, 2012). Technological innovation systems studies have defined the formative phase as the testing of multiple conceptual designs, establishing confidence in a new technology, settling towards a consensus in design;
2. An ‘up-scaling phase’ where designs, having reached convergence upon the best technical solution, will see significant increases in unit capacities as technologies continue to push the boundaries of plant size. Simultaneously, an increase in the number of units deployed is also likely to take place (Wilson, 2012);
3. An ‘industry growth phase’ where large-scale deployment of larger unit capacities causes significant growth in the overall deployed capacity of the technology (Wilson, 2012). The growth phase will also experience market expansion, characterised by a growth in the market, learning-by-doing and scale economies (Jacobsson and Bergek, 2004; Jacobsson *et al.*, 2004). It should also be noted that within the growth phase, deployment of technologies occurs both at and below the device capacity limit.

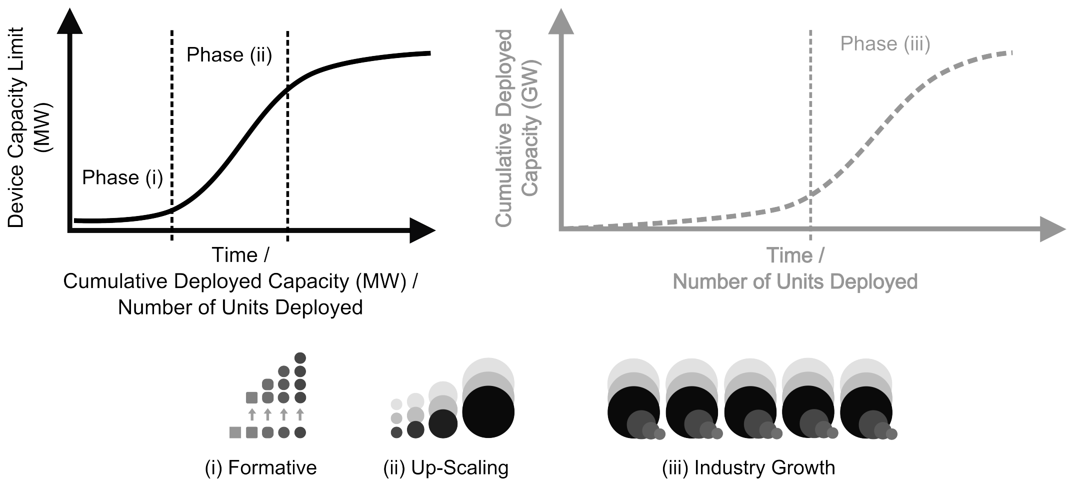

Figure 3.3: Representation of the three phases of technological development at unit-level (left) and industry level (right).

Logistical growth functions have been used successfully to characterise the development, growth (at both unit and industry level), and saturation of energy technologies with respect to timescale associated with each phase of development, including steam turbines, gas turbines and aviation jet engines (Wilson, 2012). The formative phase of technological development is a crucial stage in the technology life cycle, and should not be overlooked. A diagrammatic representation of the three phases of technology development, considering both unit-level and industry-level growth can be seen in Figure 3.3. Energy technologies have followed a similar trend requiring the construction and installation of many (often small scale) units, over a prolonged time period – often lasting for a number of decades (Wilson, 2012) – prior to the emergence of successful industrial commercialisation. Many competing technologies in competition for access to limited markets, with highly uncertain policy and regulatory regimes are characteristic of the formative phase (Jacobsson and Bergek, 2004).

The formation of a market is a pre-requisite for future advancement of new technology: a space in which learning processes can take place within a protected environment, with the support of government subsidies bridging the gap between technology R&D and prospective future markets (Jacobsson and Bergek, 2004). The entrance of technology developers and companies exploring the possibility of taking an active role in the development of new technology, and the role that policy alignment plays in supporting these technologies in the formative phase is well documented in the literature (Jacobsson and Bergek, 2004).

Government support for electric vehicles in the UK was developed through a number mechanisms. Initially, a £5000 grant towards the purchase of the first 15,000 electric vehicles in the UK provided an incentive to consumers, and made the cost to consumer more competitive with combustion engine alternatives, an attempt to kick-start the market. Congestion charges for combustion engine vehicles, the implementation of numerous free charging points and free parking for electric vehicles within a number of city centres provided further attractive qualities.

The uncertainty surrounding future development and commercialisation of a new innovation increases the risk associated with involvement in the formative phases of technology development. Securing early adopters and accessing early deployment in order to refine future iterations results in an often lengthy process before mass consumer uptake (for example, consider hydrogen fuelled car development, which was the topic of much interest in the 1990's, but 20 years later is still very much limited to niche markets and R&D). These parameters often limit the unit scale of new technologies, until iteration, modification, and adaptation to market demands allows the emergence of proven and reliable technology with convergence upon a superior solution (Jacobsson and Bergek, 2004; Wilson, 2012). Successful emergence from a formative phase will see industry level growth, often after a substantial increase in the number of small-unit deployments (Wilson, 2012). It should also be noted that observation of several industries has suggested that R&D refinement of technology still takes place during the initial diffusion and widespread adoption of a technology (Wilson, 2012).

Within the energy sector, the up-scaling phase is characterised by unit growth, as economies of scale and materials advances permit the design and manufacture of larger unit capacities. This fosters greater levels of power production per unit installed. The rate of up-scale has varied historically between technologies, as has the timing at which the up-scaling process initiates. Typically, the up-scaling process can last decades (Wilson, 2012).

The industry growth phase again sees large numbers of unit deployments, but large unit capacities pushing the boundaries of capacity limit may dwarf the small unit capacity deployments of earlier phases. However, in addition to deployment of units at the capacity limit, it is often seen that deployments of units at smaller scale will also continue. The time-frame associated with the up-scaling phase varies due to the pull from different forces – the economies of scale suggesting that larger unit capacities are more cost effective is countered by a non-uniformity in demand across alternative market segments providing a market for various technology scales (for example community scale wind power vs. utility scale wind power).

In order to make the transition from invention to innovation, there is a clear dependency between the diffusion of technology and the need for a defined formative phase to smooth early flaws. Iteration of technology allows the development of superior performing models, and the necessary confidence in ability of the technology to perform according to design parameters.

3.4.4 Technological Change – Gaps and Opportunities

Observations within the literature review of research on the topic of ‘Technological Change’ within Sections 3.4.1, 3.4.2, and 3.4.3 has identified a gap, which this thesis can undertake to answer. Much work exists investigating the timescales associated with technological change across a number of technologies and industries. Diffusion of innovation, adoption of new technologies, and displacement of old technologies has been considered within this literature review, however each example is considered with regards to changes over time or with regards to increasing cumulative deployed capacity – a means of conveying cumulative experience gained. From an engineering perspective, there is a substantial gap in the field of research with regards to the number of unit iterations that take place over a given phase of development. James Dyson, inventor of the first bag-less vacuum cleaner, said of failure:

> "I made 5,127 prototypes of my vacuum before I got it right. There were 5,126 failures. But I learned from each one. That's how I came up with a solution. So I don't mind failure."

If the innovation process requires the optimisation of an invention prior to the emergence of a comercially viable technology, then it is plausible that many iteration attempts will be required before the invention is perfected (or, perhaps more appropriately, a minimum viable product is reached). In that respect, the variable of interest is not time, nor cumulative installed capacity; it is the number of iterations required between first deployment and eventual unit up-scaling, or between the first unit deployment and the subsequent growth of the industry.

There is no body of work, to the author's knowledge, that explicitly investigates this issue within historic energy sector technologies, nor within the development emerging wave and tidal energy technologies, and therefore this represents a new area of research in which this thesis can contribute. Investigation of this will therefore provide unique added value and contribution to the body of knowledge within the energy sector.

Logistic growth functions have been used to characterise the timescale associated with technological change, and it was conjecture in this research that a similar process, using 5PL functions, could be used to model technological change over a number of unit iterations. If proven, this will allow inference of unit iterations within the formative phase of technology development for a number of energy sector technologies. This technology trajectory could then be compared to the trajectory being attempted by wave and tidal stream energy technology development.

It was anticipated that this area of research would be able to provide enhanced understanding of issues surrounding technology scale, particularly with regards to the dichotomy identified in wave and tidal energy over the use of small-scale or large-scale technology within the development, demonstration and optimisation process.

3.5 Learning Theory

The use of a 'learning curve' to represent technological change emerged after the discovery by Wright (1936) that the labour costs associated with aircraft manufacture decreased in relation to increasing levels of cumulative production. More recently, learning curves have become a focus within future technology analysis and policy documents (Junginger *et al.*, 2010a; Jamasb and Köhler, 2007). The learning curve has achieved a prominent role in assessing future technological options within the energy mix (Carbon Trust, 2011; Junginger *et al.*, 2010a; Callaghan and Boud, 2006; IEA, 2000). The impact of cost reduction through learning often correlates with the diffusion of innovations, therefore this makes the study of both subjects of particular interest within this research.

Learning rates, and the learning curves that can be produced, allow representation of gains and improvements in process industries through 'learning by doing'. Repetition of operational procedures within a specific process can result in reductions in both the time and cost associated with task completion. The term 'experience curve' is used to give further contribution beyond learning improvements within a process, to include additional types of learning – such as learning within research & development, or improvements to supply chain coordination and organisation (Junginger *et al.*, 2010a). Ultimately, experience curves can be used to explain the cost reduction associated with a given technology that is often seen as cumulative experience (in terms of number of units produced or deployed) increases. The learning rate is the percentage unit cost reduction that is associated with each doubling of cumulative production or capacity.

For technologies in which costs are currently higher than a desired benchmark, learning is often used as a way of expressing future cost reduction in order to meet future cost objectives. Learning curves are best placed to carry out retrospective analyses of observed cost reduction trends, however, experience curves are permissible for use as a technology forecasting tool, giving insight to plausible cost reductions and the associated 'learning investment' required to commercialise an emerging technology (Alberth, 2007). It is widely recognised in literature that extreme care must be taken, due to the the multiple uncertainties and sensitivities involved in the learning investment calculation (Junginger *et al.*, 2010a; Alberth, 2007; Neij *et al.*, 2003). Uncertainties and sensitivities may include discontinuities in learning over time, which would occur as a result of a major technological breakthrough (Neij *et al.*, 2003; Mueller *et al.*, 2009), or indeed the uncertainty associated with estimates in underlying data. Given the concerns outlined, learning curves should be used in conjunction with other tools whenever possible, such as trend analyses, engineering assessment and judgemental methodologies (Neij *et al.*, 2003; Mueller *et al.*, 2009).

As is found in the literature (Ferioli *et al.*, 2009), the simple experience curve formula can be written in the following form:

$$C(x_t) = C(x_0) * (x_t/x_0)^{-b} \tag{3.3}$$

where x_0 is the cumulative production or capacity at time $t = 0$; $C(x_0)$ is the cost of the unit produced at time $t = 0$; x_t is the cumulative production or capacity at time t; $C(x_t)$ is the cost of the unit produced at time t; and b is the learning parameter. The Learning Rate (LR), which is expressed as a percentage value, can be calculated using Equation 3.4. The resulting cost reductions associated with increased levels of deployment can then be represented using a simplified single factor learning (or experience) curve, as shown in Figure 3.4.

$$LR = 1 - 2^{-b} \tag{3.4}$$

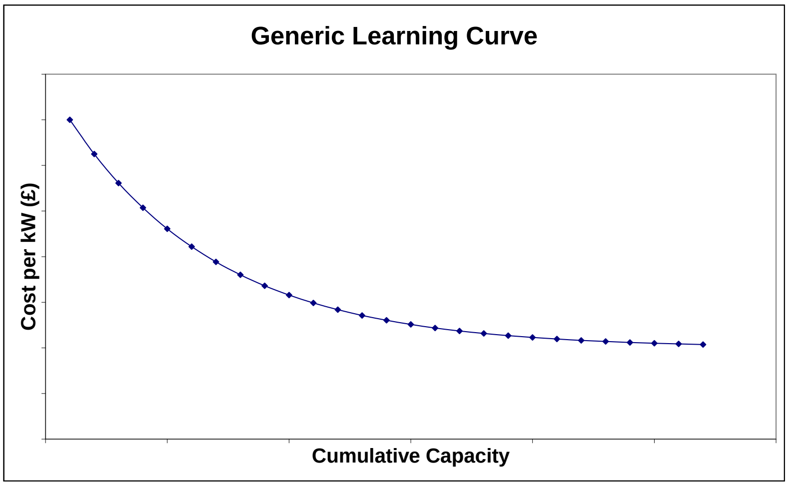

Figure 3.4: Generic single factor learning curve

Care must be taken when adopting learning curves for scientific analysis (Neij, 2008; Ferioli *et al.*, 2009). The levels of data available should cover at least two orders of magnitude of deployment in order to be able to appropriately estimate trajectories (Ferioli *et al.*, 2009), otherwise a risk of estimating an over-optimistic learning rate exists. A range of energy technologies including thermal power plant (such as coal and gas) and renewables (including solar PV and wind), and the historical learning rates associated with their deployment have been presented in the literature. As demonstrated in Figure 3.5, pulverised coal power plant saw learning rates of approximately 8%; natural gas CCGT had a negative learning rate (cost increase) between 1975 and 1990, and then a learning rate of approximately 25% (between 1990 and 1997); solar PV saw learning rates of approximately 20% between 1970 and 2006; and onshore wind saw learning rates of up to 15% (Mcdonald and Schrattenholzer, 2001; Rubin *et al.*, 2015).

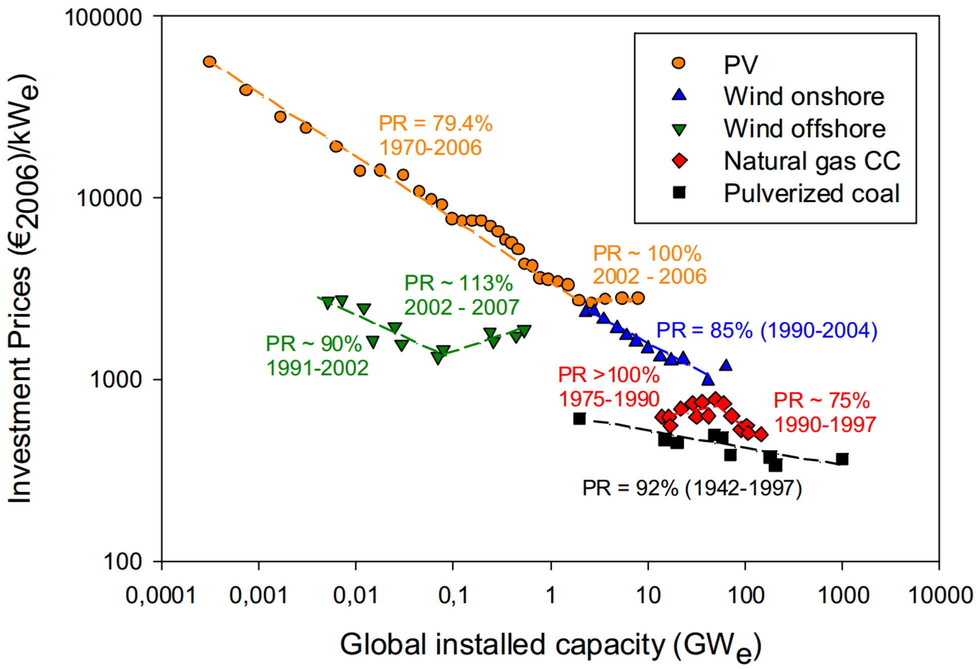

Figure 3.5: Learning rates within energy technologies (Junginger *et al.*, 2010a)

3.5.1 Learning Investment

As discussed in Ferioli *et al.* (2009), learning curves can be used as a tool to investigate the level of investment required in order to bring a new technology to a level of cost-competitiveness with incumbent technology. This tool is particularly useful in energy policy, whereby new low carbon technologies may offer the benefit of reducing carbon emissions, but at a cost that is currently uncompetitive with established technology. If the costs of a nascent technology can follow an appropriate cost-reduction trajectory, then in time they will become competitive with the wider market. This has the ability to influence the support mechanisms that will be used to assist low-carbon technology development – both in terms of financial value, and duration through which support mechanisms are offered. Two terms will be used frequently throughout this analysis, '*total investment*' and '*learning investment*', which are defined below.

The **total investment**, in the context of this research, is the total amount of financial resource that has been committed into technology deployment to reach the total cumulative installed capacity at a given point in time. While, under ideal circumstances, the total investment should also include any financial resource that was provided for R&D purposes, in practice this data is difficult to obtain without a high degree of uncertainty, so this research has considered the cost of deployment only.

The **learning investment** is the additional investment needed to support a new technology, which is achieving sustained cost reduction with increasing levels of cumulative deployment, to reach a break-even point with established technology. This is an additional cost over and above the total investment associated with the deployment of a more established and cheaper alternative (Ferioli *et al.*, 2009). The learning investment can be obtained by subtracting the total investment costs of an incumbent technology from the total investment costs of the new technology, represented diagrammatically in Figure 3.6. This figure shows a technology progressing down a learning trajectory to reach cost competitiveness with an incumbent technology. C_0 represents the starting cost (in £/kW) at a cumulative capacity x_0 (in MW); C_b represents the break-even cost of the technology and occurs at a cumulative deployment x_b. The learning investment is significantly impacted by three key parameters, as discussed in MacGillivray *et al.* (2013b):

1. Starting cost (SC) in £/kW;
2. Learning rate (LR), expressed as a percentage;

3. The capacity at which sustained cost reduction effects are seen to take place (CSCR), expressed in terms of deployed capacity or number of deployments.

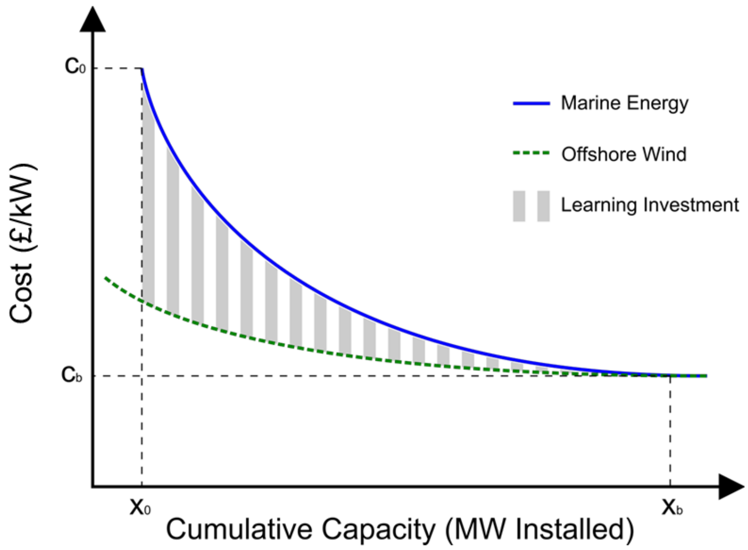

Figure 3.6: Graphical depiction of learning investment.

While significant consideration is given in the literature to the need for cost reduction, and the impact of the learning rate on overall technological progression, the level of capacity installed prior to significant cost reduction taking place cannot be overlooked. The installed capacity at the initiation of cost reduction is one of the fundamental parameters needed to calculate the learning investment (Ferioli *et al.*, 2009). It has been shown that even small variations in the above mentioned parameters can have a dramatic effect on the overall level of learning investment required to secure technology cost-competitiveness (MacGillivray *et al.*, 2013b).

The learning investment for gas turbine power generation technology supplied by General Electric, relative to incumbent coal power plant, has been estimated to be around $5 billion (Grubler *et al.*, 1999). This covers the time period between 1958 and 1980 – the first commercial application of gas turbines in power plant through to reaching commercial competitiveness with coal power. Further examples of learning investment can also be seen in the literature (Ferioli *et al.*, 2009).

3.5.2 Learning Theory – Gaps and Opportunities

It has been identified that care must be taken when using learning rates; in particular, a recommendation has been presented that suggests the levels of data available should cover at least two orders of magnitude of deployment (i.e. at least units 1 to 100; 10 to 1,000; 100 to 10,000 etc.) in order minimise the risk of synthesising an over-optimistic learning rate. However, it is also suggested that learning curves can be used as a tool to investigate the learning investment for a given technology. Despite the limited levels of deployment experience in wave and tidal energy to date, learning curves are used prolificly in the marine industry reporting as a means of expressing trajectories towards more attractive costs (Carbon Trust, 2011; SI Ocean, 2013). However, scenarios typically represent attractive case studies, with little or no means of validating the choice of input parameters used. Deployment encompassing over 100 units is not available within the ocean energy sector. Given this lack of validation, it would seem appropriate that an uncertainty analysis of plausible trajectories and learning curves (and subsequent learning investments) could be a useful indicator that explicitly identifies the impact of the economic uncertainties that exist within the wave and tidal energy sectors .

If wave and tidal energy is to be successful at a commercial level, then it must become cost competitive with alternative sources of energy, or, at the very least, present attractive qualities that justify additional expense over and above alternatives. For many potential investors, the high current cost of ocean energy is a barrier to further investment, and the costs must demonstrate significant reduction in order to appeal to the private sector investment community.

A number of industry reports present CAPEX costs for wave and tidal energy converters and make claims on plausible learning rates for the sector (Callaghan and Boud, 2006; Carbon Trust, 2011). However, no detail is provided on the implication of minor deviation from assumed input parameters, nor the overall economic cost to achieve cost competitiveness with a given benchmark or target. A gap in knowledge exists to analyse the learning investment of wave and tidal energy, based on a sensitivity analysis of the key parameters of SC, LR, and CSCR. In particular, this analysis could be used to compare costs with the offshore wind energy sector, a suitable benchmark for wave and tidal energy, in order to make explicit the level of financial risk and uncertainty that is currently present within the research, development and innovation environment of wave and tidal energy.

3.6 Chapter Conclusion

This innovation review has outlined innovation from the perspective of academic literature, revealing that innovation is not the invention of a new product or process, it is the successful transition to commercial application of a given product or process, leading on to wider diffusion of the invention. The innovation review has successfully demonstrated elements of innovation theory that can be used to gain a deeper understanding of the research, development and innovation trajectory for wave and tidal energy technologies and identified gaps in the current knowledge that this research has addressed.

The innovation review has demonstrated that innovation and the establishment of wider diffusion is a function of deployment. However, much of the literature observes historic trends over time, ignoring the important aspect of unit iteration. The three phase process of diffusion will have an impact on the cost and likelihood of continued economic support. There is a need to consider the background of other technologies within the energy sector, and heed the warnings that could be provided by these historic development pathways, particularly with regards to the number of unit deployments that take place at each stage in the development process. This has provided a benchmark in which to compare wave and tidal energy technology development. Diffusion of innovation can be modelled using multi-parameter logistic functions, and therefore this approach is considered to be appropriate for further investigation, using unit iteration as the variable of interest rather than time. This approach will also provide a methodology for answering the small-scale vs large-scale dichotomy present within technology development in the wave and tidal energy sector, and provide justification for the most appropriate approach for innovation in this sector.

The innovation review has also identified, within the scope of the considered academic literature, the validity of learning curves as a tool to estimate the plausible learning investments required in bringing a technology to a level of cost competitiveness with alternatives. This tool will be utilised within Chapter 5 of this thesis to demonstrate the uncertainties that currently exist in the ocean energy sector, through minor deviations in input parameters and the overall impact that these deviations have on the economic requirements for the sector. Potential step-changes that could dramatically alter the costs associated with the development and deployment trajectory will also be considered from a learning investment perspective.

Chapter 4

Analysis of Diffusion of Innovations in Energy Technologies

4.1 Chapter Introduction

This chapter provides an analytical approach that answers the technological research questions identified for this thesis in Chapter 1. It presents a new argument to identify the trajectory that should be pursued in technology research, development, and innovation within the wave and tidal energy sectors.

Although including a diverse range of complex engineering processes and machinery, technologies utilised within the power generation sector have been seen to follow certain similar trends in their technological development. As shown in Chapter 3, historical evidence and existing literature points to a 'formative' phase in the early stages of technological development within the innovation process. In this formative stage, the formation of niche markets and creation of a safe protected environment to carry out early deployments will help to facilitate the learning process and improvement of the price-to-performance ratio of the technology under development (Jacobsson and Lauber, 2006). Comprehensive development, iteration and optimisation can be expected within the formative phase before a successful technology upscales and achieves significant market diffusion.

Much innovation systems research has focused on the formative phase, and has stressed the need for policy support to emphasise 'variety rather than volume'; on smaller-scale testing rather than seeking scale economies (Jacobsson *et al.*, 2004). The value of iteration should not be overlooked.

Utility companies and end users of electricity generated from power generation technologies can receive benefit from the use of large-scale technology, as this can be considered to directly correlate with larger levels of power production, increased revenue, and lower Levelised Cost

Of Energy (LCOE). However, the route to successful technology optimisation is not reached through the demonstration of a single unit prototype, or small samples of production; rather, successful technology is demonstrated through the iterative process of experimentation and optimisation, in order to understand systems and sub-systems that perform well, and those that do not (Thomke, 2003). Prototype costs are invariably significantly more expensive than the end commercial product, but cost reduction trajectories have been demonstrated historically in a number of energy sector technologies (Jamasb, 2007).

4.2 Technological Innovation: Theory and Practice

Diffusion is not an instant process, and as such, the element of time is often regarded as an essential factor in the theory of diffusion (Rogers, 1995). This is accurate, as diffusion generally requires the transfer of knowledge between different actors in a system, exemplified even from the earliest work in diffusion studies such as the diffusion of hybrid corn seed in rural agricultural communities in the USA (Ryan and Gross, 1943), the acceptance of which naturally takes time to propagate. However, from an engineering perspective, the technological development and innovation in mechanical systems that we seek to evaluate in this study are more directly a function of iteration and technological evolution through unit deployment. This innovation development by its very nature cannot occur over time alone without physical production and deployment of technology, just as the process of cost reduction through learning is a function of unit deployment and not a function of time (MacGillivray *et al.*, 2014).

For example, we cannot expect to see technological evolution and diffusion of electric vehicles to take place if electric vehicle manufacturers were merely to make one prototype then store it in a garage for a prolonged period of time, inviting marketing experts and photographers to heavily publicise the perceived merits of their innovation for diffusion, as they wait for it to commercialise. Developers of electric vehicles are required to operate, test (often multiple prototypes), and utilise critical feedback in order to allow refined development of future commercial models that meet the needs and requirements of the intended customers. Increasing volumes of production are also likely to unlock cost savings for future consumers, attracting a larger audience for diffusion of the innovation.

Similarly, for energy technologies, diffusion of innovation cannot be expected to occur through the deployment and operation of single unit prototypes without additional deployment of improved iterations of the technology. Thus the method proposed in this research was to use 5PL growth functions to evaluate increases in maximum unit capacity (unit-level growth) and cumulative deployed capacity (industry-level growth) with respect to cumulative number of units deployed. Of course, unit deployments occur over time (and in the case of this research, the deployment of technology was catalogued chronologically prior to carrying out the analysis), and so the requirement of a time-factor within the process was still met, albeit indirectly. Each subsequent deployment takes place at an irregular time interval. The novel contribution provided by the approach suggested in this research is to reveal an enhanced level of detail, which can identify the level of unit iteration that took place within the given time frame of a formative phase.

The methodology proposed that analysis of historic energy sector technologies will lay the foundational understanding of technology development within the energy sector, and the technology trajectories and innovation pathways that have been followed historically within the development of select energy generating technologies could provide valuable insight into appropriate research, development and innovation trajectories for novel ocean energy converters. By investigating a range of power generation technologies, from fossil fuel to renewable, trends and patterns can be identified and discussed. While the wave and tidal energy sector operates in a distinctly different environment from many of these technologies (at sea, in harsh, unforgiving, and remote locations that are difficult to reach), consideration of historical evidence may provide justification for adapting current or anticipated development pathways and trajectories for ocean energy technologies. The technologies that have been selected for analysis in the research reported for this thesis include steam turbines (within coal power plant), gas turbines, solar photovoltaic (PV) arrays, and wind turbines.

The chosen technologies have different capacity (or load) factors, and it should be clarified here that each technology functions differently – there are limits associated with the operation of each technology. The capacity factor is considered to be the ratio of the actual power output from a power plant and the maximum permissible power output if the plant was to operate at 100% load over a given period of time. The Digest of United Kingdom Energy Statistics 2016 provides the relevant data for calculation of capacity factors within the UK energy mix (Department for Business, Energy and Industrial Strategy, 2016). For coal power plant (steam turbines), the load factor was as high as 58% in 2013, but was 39% in 2015; gas turbine power stations in the UK had a maximum load factor of approximately 48% in 2011, but the load factor was approximately 32% in 2015; offshore wind has a load factor approaching 40%; and onshore wind has a load factor of between 25% and 30% (Department for Business, Energy and Industrial Strategy, 2016). Solar PV load factors vary with geographic location (peaking between 15 and 35 degrees lattitude), ranging from 6% to 25% (Andrews, 2014). It is estimated that the load factor for wave and tidal energy technologies could be in the region of 30%, but this is to be demonstrated through long term operation.

Within the technology types, access to data within specific geographic regions directed the core market focus of the technology, limiting each technology analysis to a single country rather than global deployment levels. Whilst this resulted in an inability to capture wider market dynamics, the data did cover principal or core regions of development and deployment, so can be considered to be representative of the early or formative stages of technology development in each case.

Steam turbine, gas turbine, and solar PV technology data has been obtained from the US Energy Information Administration's Annual Electric Generator dataset, which is available online (US Energy Information Administration, 2015). In the case of steam turbines, data was supplemented by known early developments in steam turbine design recorded in the literature (Baumann, 1912, 1921). Data for individual steam turbine and gas turbine technology had to be extracted from the source material, which consisted of a register of all power generation sources within the US power generation portfolio, active, decommissioned, and in planning. Data for wind turbine technology was located in the Danish Wind Turbine Master Register, a database that is updated monthly and is available online (Energi Styrelsen, 2014).

For each technology case, the data had to be arranged in order of installation date, forming a chronological catalogue of each deployment of a given technology. Additional data had to be defined for all technologies to record the unit deployment number, and the cumulative installed capacity (in GW) as deployment levels increased. Unit deployment represents the sequentially increasing number of units that have been collectively deployed, increasing until the final deployment contained within the dataset. Cumulative installed capacity was calculated through summation of the unit capacity of all unit deployments that had taken place at each instance of deployment. Furthermore, the analysis was to consider all units that had been installed, even if they have since been decommissioned.

Within this research, two specific metrics of interest are considered: Unit-level growth and industry-level growth:

- **Unit Level Capacity Growth:** The unit up-scaling of technology, represented by increases in the unit nameplate capacity (in MW) with respect to unit deployment (Note: the nameplate MW deployed reflects an individual unit, and does not equal the total deployed capacity of that techology);
- **Industry level growth:** The industry level up-scaling experienced within each technology type, represented by the cumulative installed capacity (in GW) with respect to unit deployment. This characterises the diffusion of technology into a market.

For each technology, two logistic growth functions were calculated: One to account for unit-level up-scaling (the growth in the maximum unit capacity available at a given point in time, ignoring outliers), and the second for industry level up-scaling. Logistic curves were fitted for each technology type at both unit and industry level where applicable, allowing comparisons to be made between unit and industry level growth. Of particular interest is the need to determine the number of unit deployment requirements to successfully progress through a formative phase and reach an up-scaling phase. The empirical data used to plot the logistic functions resulted in an s-curve growth function, with several important parameters for this investigation:

1. x_{mid}, the x-axis value at the point of maximum growth, taken from the point of inflection of the logistic function;
2. x_i, the x value at the point at which the unit or industry level up-scaling exceeded 10% of the difference between the initial deployment capacity and the maximum asymptote, T (or current maximum value if the asymptote has not yet been reached) – an indicator of the initiation of the up-scaling process;
3. x_f, the point at which the unit capacity reaches 90% of the maximum asymptote, T, if applicable) – an indicator that a certain capacity limit was being approached.

Several software tools were available for 5 parameter logistical curve fitting and statistical analysis, such as R (R Core Team, 2015), or open-source code for functions within MATLAB (Cardillo, 2012). However, the "Solver" add in for Microsoft Excel 2013 can be used for non-linear regression analysis (Horton and Leonard, 2005). In this case, a known equation exists (with a known number of variables, B, T, b, x_{mid} and s, as defined earlier) for which reasonable initial guesses can be provided based upon observation of the original dataset. A predicted curve was set up using these initial estimates. The predicted data was then tested for goodness of fit by comparing with the original data using the least squares method, in which the square of the difference between actual data and predicted data was calculated and then summed across the range of data points to find the Error Sum of Squares (SSE).

Using Excel Solver, a target cell was defined, in this case the SSE and the value of the target cell was minimised through iteratively applying perturbations to the five defined variables until convergence upon a solution was reached.

Plotting of the solutions for the logistic curve against the input data could provided an immediate sense check of the solutions as, if initial guesses were not adequate, the solver would not reach appropriate solutions. Visual inspection of the plotted logistic function against the real dataset was adequate to make this judgement. If it was not possible to make confident initial guesses, then use of specific software such as those outlined above would be more appropriate.

By calculating the coefficient of determination, R^2, of the predicted solution, in conjunction with a visual check of the residual plots (to ensure that the predicted curve did not exhibit significant bias), an indication of the goodness of fit for the predicted logistic curve could be presented. For this study it was to be assumed that if a maximum asymptote value, T, was not reached, or if the data was clearly indicating continued increase, then the maximum value within the dataset was taken as the limiting capacity for calculation of x_i, even if a point of inflection had not been reached. This scenario occurred if unit-level or industry-level up-scaling was still taking place at an exponential rate. For all technologies considered, with the exception of wave and tidal stream energy (where insufficient data points exist to fully establish accurate 5PL curves), the 5PL model was observed to provide a strong fit with the empirical data, once the removal of outliers had taken place.

Values for T, B, s, b, and x_{mid} were obtained through a satisfactory solution using Excel Solver (as described above), with the goodness of fit confirmed in each case through a sense check of the coefficient of determination and residual plots. The additional points of interest, x_i and x_f, were calculated through re-arranging the 5PL logistic equation and solving for x (the y-value in each case was calculated as a known function of T and B, as explained above). The equation then becomes:

$$x = x_{mid} - \frac{ln[(\frac{T-B}{y-B})^{\frac{1}{s}} - 1]}{b * ln(10)} \tag{4.1}$$

The unit level up-scaling considered only the representative technological state-of-the-art, and utilised maximum unit capacities available at a given deployment number, rather than including the entire dataset within the logistic function fit. Deployment of technology below the unit capacity limit continues to take place throughout the up-scaling and growth phases of each technology, but the interest here is in unit level growth, and therefore had to focus on the maximum unit capacities available at a given level of deployment. Data points deemed to be outliers to the general trend were removed from the dataset prior to the fitting of the logistic growth functions. These outliers generally represented prototypes with unit-capacities significantly greater than the average deployment trend, and were evident where subsequent deployment of comparable technology unit capacities did not occur in a sustained manner. These outliers can be considered as having been ‘too big, too soon’ for the given phase of development.

The objective of this analysis was to identify the conventional technology development and innovation approach followed in known mature energy technologies. The same process could then be carried out for known technology deployments within the wave and tidal energy sectors. A comparison could then be drawn between the deployment trajectories in wave and tidal energy, and the deployment trajectories observed within commercial energy sector technologies. Results from this analysis should be able to identify whether the wave and tidal energy sector is following a development model that is aligned with that of successful energy technologies.

The use of empirical data has revealed interesting trends surrounding the formative stages of technology development, and has allowed for the observance of timescales associated with the transition of an invention through formative, up-scaling and growth stages at both unit and industry level (Wilson, 2012). The formative stage can last a number of years, and in most cases, industry growth is preceded by technological consolidation around front-running technology and unit up-scaling.

4.3 Analysis

It must be emphasised that the diffusion analyses reported within this section relate to developments within 'single' markets, and do not represent a global deployment perspective or account for growth in international markets. An assumption was made that the data covered principal or core regions of development and deployment in each case. Within the analysis undertaken for this work, steam turbine and gas turbine technologies were successfully observed to reach a maximum asymptote, therefore logistic growth functions could be used to define formative, up-scaling and growth at both unit and industry level. Wind turbines and solar PV technology, however, are still in a process of unit-level and industry-level up-scaling. The data analysed suggested that wind turbine technology may have reached a point of inflection in unit-upscaling, although continued growth from current levels is still expected. However, the industry growth has not reached a similar observed long term reduction in capacity additions – exponential growth at an industry level is perhaps still being experienced with respect to wind turbine unit deployment numbers. Each technology type will now be considered in turn.

4.3.1 Steam Turbines

By the turn of the 20th century, inventors and engineers carried out much experimental work surrounding the extraction of power from steam. By this period in time, steam power was well utilised outside of power generation applications, for example transport and machinery operation in manufacture (Fouquet, 2010). However, the reciprocating piston motion, which was previously the technological state-of-the-art, was not optimised for electrical power generation. Focus was thus shifted on to directly enabling rotational motion through the use of pressurised steam. Many of the early turbine designs were based around broadly similar principles of operation (Baumann, 1912). The axial flow steam turbine invented by Charles A. Parsons in 1884 is largely considered to be the first design that influenced the commercially successful modern steam turbine (Hossli, 1969). The first Parsons turbine was capable of generating 7.5kWe. After the technological inception and early demonstration, there was significant development of different steam turbine designs, improving overall performance of early designs. In addition, there was access to enhanced knowledge on the theory of steam turbines due to much experimental work that was widely being published at the time (Stodola, 1905). An amalgamation of the specific advantages of different turbine types led to the optimisation of steam turbine technology in terms of reliability, efficiency, and cost during the early 20th century (Baumann, 1912).

By 1909, Westinghouse had developed a 15MWe steam turbine, which was provided to the City Electric Company in San Francisco (Baumann, 1912), a clear progression from the 7.5kW power output of the early Parsons design. An increase in connectivity to electrical grid systems resulted in a demand for larger power stations, which in turn led to the engineering design and fabrication of larger steam turbines (Baumann, 1921).

Construction of power plant accelerated in the late 1930s. At the beginning of the 20th century, a typical large coal power plant, with a plant capacity in the order of 50MWe, would generally consist of several 10MWe steam turbines coupled with 50-60 boilers for steam production to provide the necessary motive force for the turbines (Yeh and Rubin, 2007). The transition to pulverised fuel technology (grinding the coal to a fine grain before injecting into the combustion chamber) increased the efficiency and capability of boilers, enabling a smaller number of large boilers to be used within each power plant (Yeh and Rubin, 2007). Additional advancements in plant thermal efficiency enabled cost effective electricity production from larger plant, which removed earlier designs to obsolescence. The growth in boiler capability, improvements in thermal efficiency, and increased demand for electricity, resulted in the eventual up-scaling and growth of individual units to the GW scale that is available today.

Steam turbine unit deployments are presented as unit capacity with respect to increasing number of unit deployments (Figure 4.1), unit capacity with respect to time (Figure 4.2), and number of units deployed with respect to time (Figure 4.3). For clarity, the unit capacities are presented in MWe – the electrical power generated from the plant. The calculated logistic fit for both unit and industry level up-scaling is shown with respect to both increasing numbers of unit deployments and time. Analysis of the data revealed that significant unit level up-scaling did not become fully established until over 799 unit deployments had taken place (see Figure 4.1). The time-scale for the formative phase deployments covers a 38-year period between 1909 and 1947 (see Figure 4.2). The post-war period following the end of the Second World War saw increases in unit scale, and also in the cumulative capacity additions to the coal power station fleet.

The rate of increase in unit level up-scaling slowed after 1,543 unit deployments, reaching a point of inflection at this stage. Comparing this level of deployment with Figure 4.2, it can be seen that this point of inflection occurred around 1973. Subsequent unit growth allowed the maximum capacity to extend beyond 1GW, and the analysed data resulted in a maximum

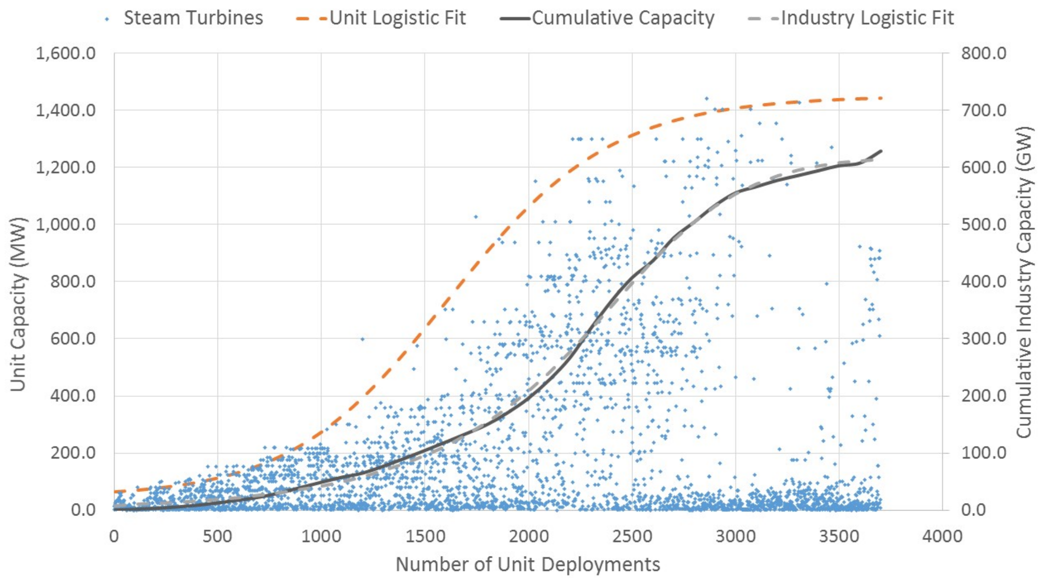

Figure 4.1: Steam turbine unit deployment and logistic fit functions

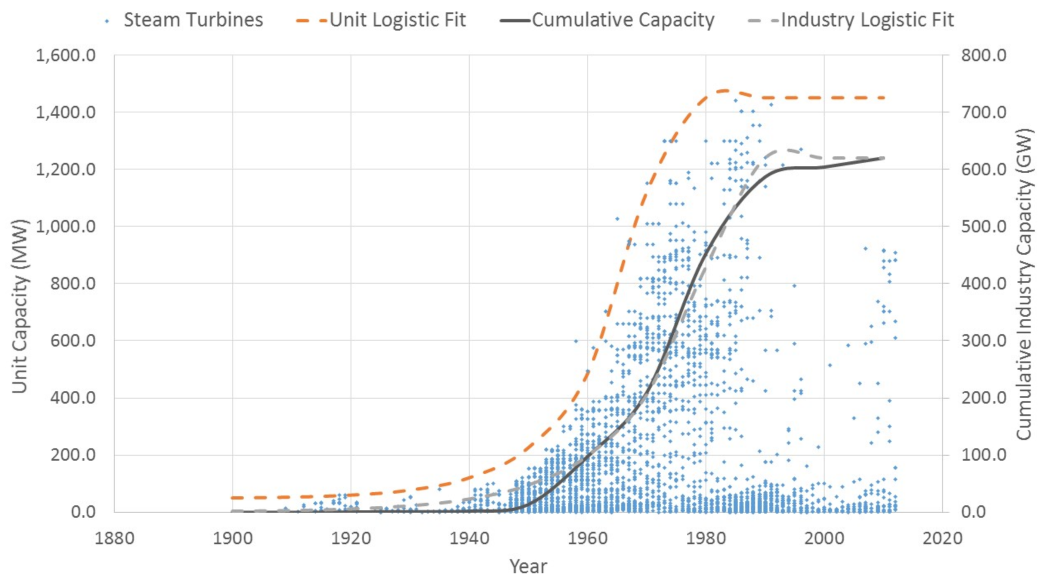

Figure 4.2: Steam turbine unit deployment over time

asymptote at 1.45GW, which was approached during the mid-1980s.

At an industry level, the cumulative capacity of steam turbine units reached a growth stage after 1,233 unit deployments according to the logistic fit model in Figure 4.1, a milestone achieved in 1958, 49 years after the deployment of the first unit. There were over 430 unit deployments between the initiation of the unit up-scaling phase and the initiation of the industry up-scaling phase within the steam turbine technology analysed, which took place over a 6-year time period.

As demonstrated in Figure 4.3, a sharp increase in the number of steam turbine unit deployments took place from around 1947. The post-war era saw new developments in production processes, including automation in production lines. Increase in domestic electricity consumption also increased rapidly during this time – electricity demand in 1950 was more than threefold the level of demand in 1935 (Morton, 2000).

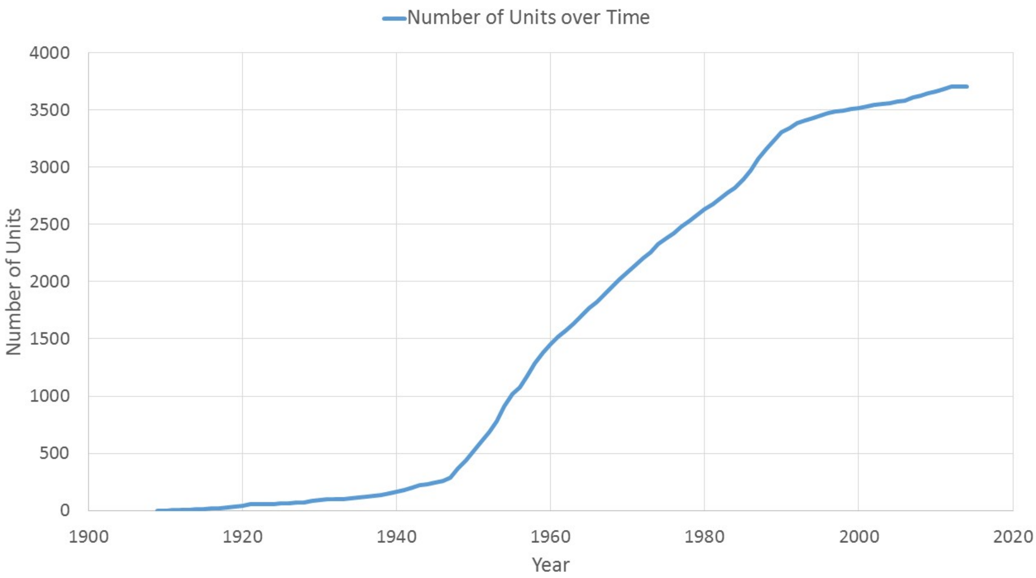

Figure 4.3: Steam turbine number of units over time

4.3.2 Gas Turbines

The gas turbine has a long and complex history, with pioneers in the late 18th century, and patents for technologies with industrial applications appearing as early as 1791 (Hunt, 1990), long before the realisation of a true gas turbine with useful propulsion or power generation qualities. In the following 150 years, much effort was made to overcome the technological challenges of high combustion temperatures and large rotational speeds; however, challenges associated with materials and lack of complementary technology prevented breakthroughs in technological advancement of the gas turbine. It was not until the optimisation of the steam turbine that gas turbine development started to make marked progress (Suplee, 1910). It has been widely recognised that the first practical application of gas turbine technology for commercial power generation was in Neuchâtel during 1939 (Hunt, 1990; Eckardt and Rufli, 2002). The 4MW gas turbine at this plant was designed and fabricated by A. B. Brown Boveri in Baden, Switzerland.

The development of the gas turbine draws from many industrial advances in complementary technologies such as compressors, advanced materials and coatings. Significant research and development took place within the industrial, naval, and aviation industries; much cross-transfer of knowledge was able to take place – resulting in the gas turbine becoming one of the most widely used and versatile power generation technologies at a range of scales from tens of kWs through to multi-Megawatt (Hunt, 1990). The dataset considered herein does not reflect this external development and we consider only gas turbine applications within thermal power generation plant in the core market region of the US.

Despite the continuing increase in unit capacities, from the 1980s onward the need to up-scale in unit capacity in order to achieve greater economic performance was no longer a factor; improvements in performance and efficiency of lower capacity gas turbines allowed for economic power generation even at power plant capacities as low as 400MW (Edinger and Kaul, 2000). Advances in materials technology, advanced coatings, improvements in cooling system and compressor capabilities allowed an increase in the thermal efficiency of the gas turbines from around 15% to over 45%, leading to rapid up-scaling of gas turbine capacity (Boyce, 1996). Gas turbines derived from the aerospace industry also have the capability to perform efficiently at low capacities such as 10MW (Edinger and Kaul, 2000), finding use in specific applications such as rapid response power generation for peaking capacities.

Data for gas turbine technology contained a number of outliers that impacted the fit of the logistic growth functions. Observation of this data suggested that these particular data points did not reflect successful unit level growth when considering the remainder of the industry development and deployment trajectory, as the early large unit sizes did not achieve subsequent deployment of equivalent technology scales until a significantly larger number of unit deployments had taken place. The outliers represent gas turbine technology that attempted to go too big, too soon. Therefore, the decision was made to remove any data point from the analysis that consisted of a unit capacity greater than 50MW prior to the 750th unit iteration. This resulted in the removal of 20 data points within an overall dataset of 3,606 units.

Analysis of the data revealed that significant unit level up-scaling did not become fully established until after 759 unit deployments had taken place (see Figure 4.4). Comparing this deployment with Figure 4.5, the formative phase spanned a 23-year period between 1948 and 1971. Observation of the data in Figure 4.5 clearly shows that the formative stage of technology

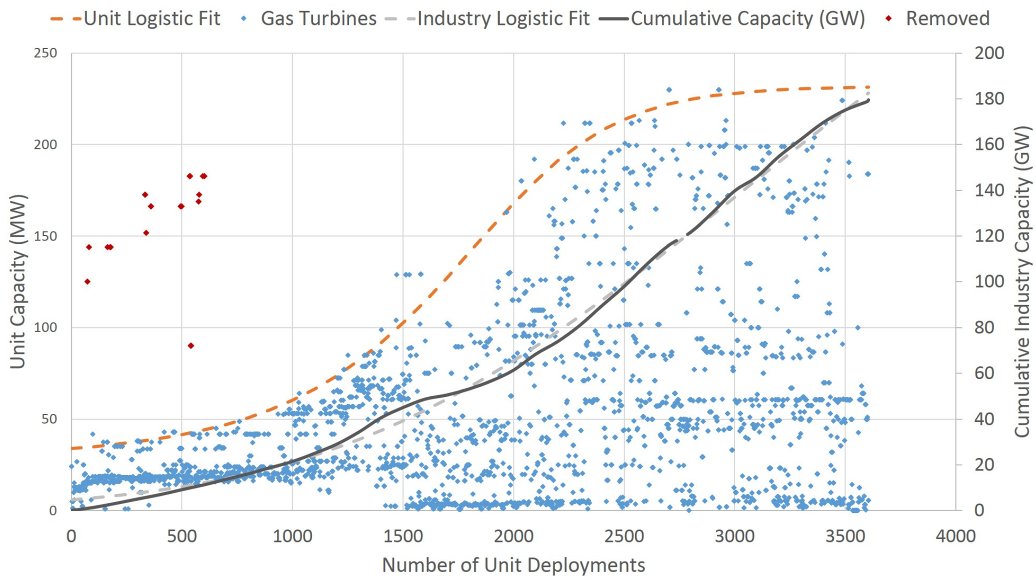

Figure 4.4: Gas turbine unit deployment and logistic fit functions

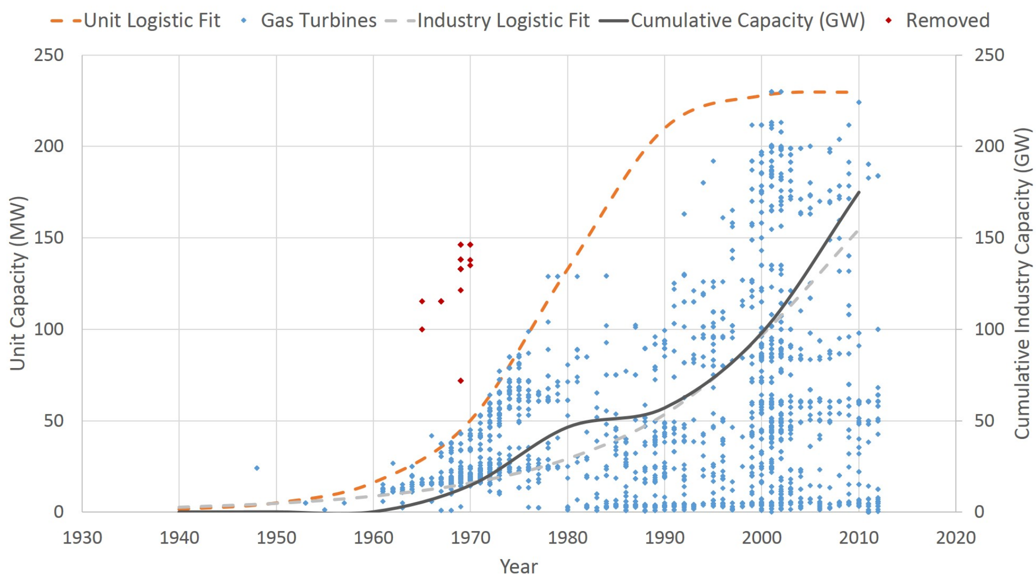

Figure 4.5: Gas turbine unit deployment over time

development was dominated by deployment of technology below that of the capacity limit at the time – the majority of units deployed being of unit capacity in the region of 20MW – even before unit-level up-scaling became fully established. The rate of increase in unit level up-scaling slowed after 1,994 unit deployments, the point of inflection, and the trend results in a clear asymptote at 232MW. The data suggests that the asymptote was converging upon the maximum in the early 2000s.

At an industry level, significant up-scaling became fully established after the deployment of 887 units, 128 units after the establishment of significant unit-level up-scaling – however this milestone was also achieved in the early 1970s. Industry level growth is still being experienced, as no upper asymptote was apparent within the dataset. However, a point of inflection has been reached in industry level up-scaling.

The number of unit deployments plotted on a time axis show a rapid increase in the number of gas turbines constructed between 1967 and 1973 (see Figure 4.6). This occurred concurrently with a rapid growth in gas turbine unit scale. In the 1960s gas power plant efficiency exceeded 40% thanks to the advances in combined cycle operation (Hunt, 1990). Technological advance resulted in the gas turbine, in conjunction with heat recovery from the exhaust gases to provide high pressure steam for a conventional steam turbine, outperforming coal power plant in terms of plant thermal efficiency. This made gas turbines the most efficient form of fossil fuel power generation in terms of conversion efficiency from fuel source to electricity, with a reduction in generating costs and overall life cycle costs. Advances in material capabilities allowed for the ability of compressor blades to tolerate increasing compression ratios and turbine inlet temperatures, and turbine blades that could withstand operation within higher exhaust gas temperatures, further improving performance and efficiency (Hamdia Afgan and da Graca Carvalho, 2002).

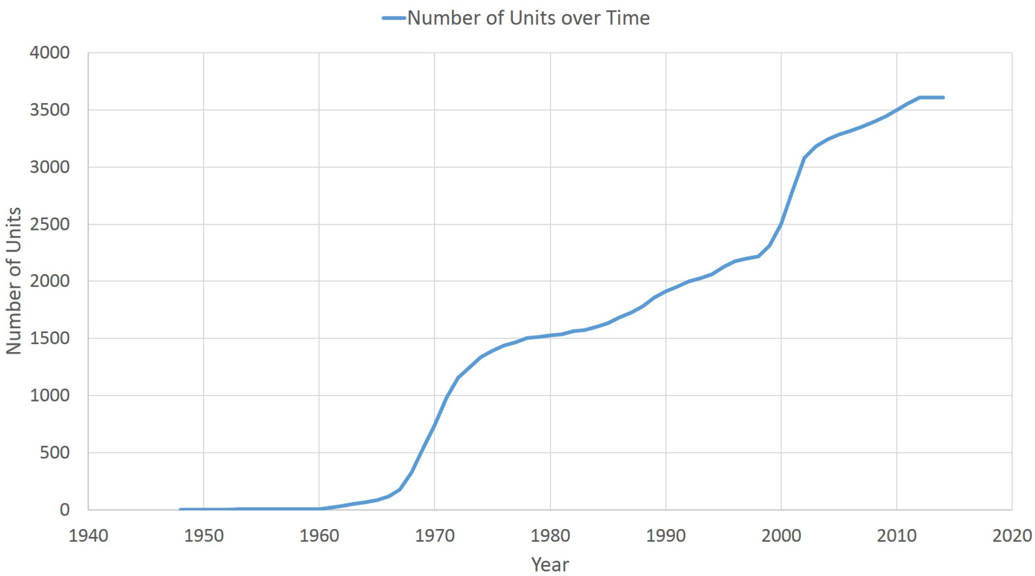

Figure 4.6: Gas turbine number of units over time

From 1974 onwards, gas turbine deployment continued, albeit at reduced levels of growth, but in 1999 a second rapid increase in the number of gas turbine unit deployments took place.

Liberisation and deregulation of the electricity markets created a 'gas bubble' during which many unit installations took place globally (Eckardt, 2014). The relative low cost of gas turbine power plants compared to alternatives was attractive to many of the new players within what were, at that time, recently deregulated markets. The rate of construction of new gas turbine power plant slowed from 2003 with increases in gas price, and general gas price volatility (Breeze, 2014).

4.3.3 Wind Turbines

Several national government funded research programmes for wind turbines resulted in the deployment of a number of large-scale prototypes between 1980 and 1988, including the MAN GROWIAN (Germany), the Howden LT-1 (UK), the NIBE A, NIBE B and the Tjaereborg Wind Turbine (Denmark), and the MOD 1 (USA) whose rotor diameters and rated capacities are shown in Table 4.1.

By the 1980s, a rich history of aerodynamic expertise from advancements in aviation was present globally. Aviation was by this time a mature industry, with a wide body of knowledge in the field of aerodynamics. Proponents of the large-scale wind turbine test programmes believed that aerodynamic knowledge would be directly transferable to applications in wind energy, thus heavily influencing certain research programmes (Garrad, 2012; Heymann, 1998; Gipe, 1995). Such beliefs led to the allocation of research funding to the testing of what, at the time, were very large devices with power output in the order of Megawatts, and rotor diameters of tens of meters. The view at the time of the national research projects was that only large-scale multi-megawatt devices would be able to contribute to national power generation in an economic manner. In the UK, the Department of Energy support favoured this high-risk, commercially uncertain and highly expensive route of development (Price, 2006). This route was also the mainstay of early wind energy research programmes in the USA, Germany, Sweden, and, to an extent, Denmark (Garrad, 2012).

Ultimately, the early large-scale devices that dominated the research programmes failed to achieve significant impact on the initial development of a successful, and sustainable, wind energy industry (Garrad, 2012). Although there was transferable experience from other sectors, when put into practice this did not provide a workable solution. Fraught with failures and technical difficulties, the expense of corrective procedures for large scale turbine research programmes was unsustainable and uneconomic (Gipe, 1995). By the eventual termination

Year	Country	Turbine Name	Rated Power (kW)	Rotor Diameter (m)
1979	USA	MOD-1	2,000	61
1980	Denmark	NIBE A & B	630	40
1983	Germany	GROWIAN I	3,000	100.4
1987	UK	Howden LS-1	3,000	60
1988	Denmark	Tjaereborg (Esberg)	2,000	61.1

Table 4.1: Large scale national wind turbine R&D projects (Source data: British Wind Energy Association (1982); Van Grol and Bulder (1993))

of the government research programmes in Denmark, Germany, USA, and the UK, significant expenditure had been consumed, as shown in Table 4.2.

Country	Duration	$ million (1990)	£ million (1991)	£ million (2014 equivalent)
Denmark	1975-1988	19.1	—	21.8
Germany	1975-1988	103.3	—	431
USA	1975-1988	427.4	—	488.3
UK	1978-1991	—	55	103
Total				731.1

Table 4.2: Government wind turbine R&D expenditure (Source data: British Wind Energy Association (1982); Van Grol and Bulder (1993))

Research programmes in the USA, Germany, and the UK cost significantly more than the R&D programmes of Denmark, but they achieved significantly less (Karnœ, 1990). In fact, the intense funding towards sophisticated top-down scientific research in all countries failed to match the bottom-up approach utilised by what was, at the time, an agricultural manufacturing sector located in the heart of Denmark (Karnœ, 1990).

Although it can be argued that technological learning did take place within the early large-scale government led research projects, the products they were attempting to create did not have a market: the devices were too unreliable, too cumbersome, and too expensive for commercial interest (Jones and Bouamane, 2011). On the positive side, substantial data collection from large-scale government test projects would enable the formation of successful research facilities (such as Risø DTU National Laboratory in Denmark), and as a result would assist in the development of technical standards and device performance validation for the future wind energy sector (Garrad, 2012; Hendry *et al.*, 2010); however, the emergence of a truly commercial wind industry came around from an altogether different route.

The early wind energy research, despite being correct in terms of the eventual multi-MW scale of wind turbines, wrongly assumed that technical aerospace expertise could deliver a rapid development of large scale wind energy converter technology (Garrad, 2012)

A 'starting small' (kW-scale) approach was adopted by the agricultural manufacturing sector in Denmark during the formative stages of modern wind industry development, which allowed a productive commercial wind turbine market to evolve from grassroots beginnings (Heymann, 1998). This switch in approach in Denmark demonstrated that government support for a large-turbine research programme in tandem with favourable support mechanisms for the deployment of kW-scale devices at a community level allowed the formative development of both technology and a market (Klaassen *et al.*, 2005). Learning from the grassroots community scale device deployment through a bottom-up approach was able to feed into subsequent industry growth and commercialisation to a greater extent than the top-down scientific approaches of other national wind energy research programmes (Klaassen *et al.*, 2005).

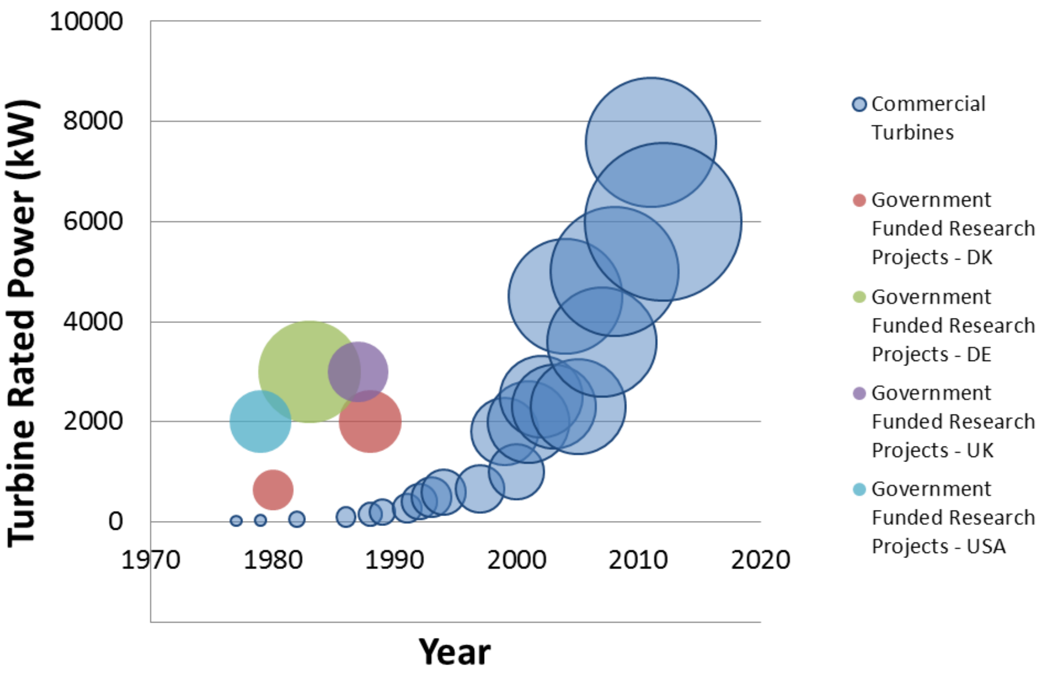

Figure 4.7: Wind Turbine Evolution (Adapted from (Garrad, 2012), additional source data: (Energi Styrelsen, 2014). Bubble size represents rotor swept area)

As demonstrated in Figure 4.7, the increase in rotor diameter of commercial wind turbines took place at a very gradual rate between 1976 and 1990. This time period saw only small iterations in the turbine capacity – increasing from 22kW to 200kW, and rotor diameters increasing from 10m to 25m; far more modest in scale than those of the national research programmes.

Between 1990 and 1997, an increase in the rate of up-scaling was seen, with the capacity limit increasing from 200kW to 660kW and rotor diameters experiencing an increase from 25m to 47m.

From 1997 to 2013, rapid increases were seen in both rated capacity and rotor diameter of the largest turbines. Exponential increases in rated capacity from 660kW to 7.5MW were seen, with rotor diameters increasing substantially from 47m to rotors in excess of 150m in diameter. A significant contributing factor to the growth of the wind industry was the influx of large engineering and equipment manufacturers from other industrial backgrounds and the effects of government policy measures, which, together with scientific research and proven capabilities in production, was able to create a step-change in the capacities of individual turbine units (Garrad, 2012).

At a global level, the trend of installed wind energy capacity is shown in Figure 4.8. A significant increase in the annual rate of deployment occurred in 1995, when the additional capacity exceeded 1GW/year for the first time. A continuing increase in the annual rate of additional installed capacity was seen until 2012 (Global Wind Energy Council, 2013).

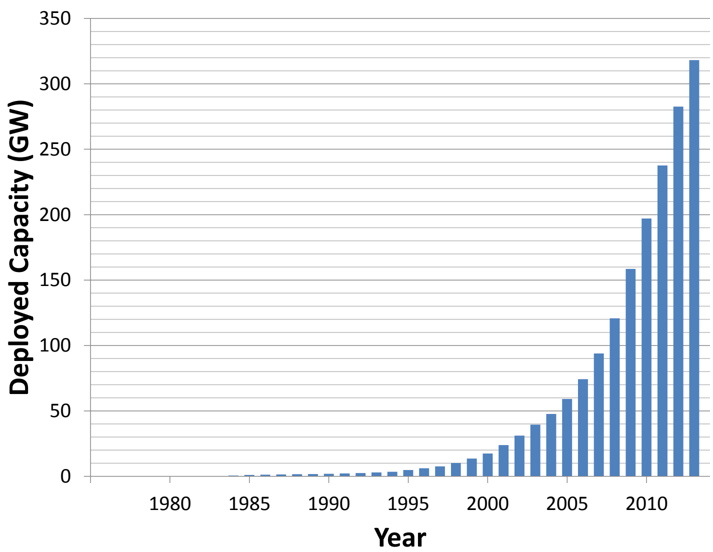

Figure 4.8: Wind Energy Global Deployed Capacity (Source data: Earth Policy Institute (2014); Global Wind Energy Council (2013))

Only after a return to small-scale turbines, with incremental development and a significant level of deployment (approximately 5GW globally), was the sector able to deliver what it had initially thought possible: large rotor, multi-megawatt turbines. As a result of this success, the rapid increase in the diffusion of wind energy in global energy systems could now see deployment of up to 1TW cumulative global capacity by 2030 (Kaldellis and Zafirakis, 2011).

Using 5PL functions for the analysis of the onshore wind energy sector in Denmark presented a number of challenges: At both a unit and an industry level, there has been no definitive inflection in the unit or industry level growth, suggesting that an exponential growth trajectory is still underway. The latest deployment evidence suggests that this growth may be tapering at industry level within Denmark, although this was not sufficient to influence a logistic growth function. Thus for wind energy, the initiation of unit-level and industry-level growth is discussed relative to the current maximum values.

In order to be enable an optimal logistic growth function that reflected the commercial deployment of wind turbines, the identification and removal of outliers within the dataset was necessary. Several assumptions had to be made that resulted in 18 of 7,971 data points being removed from the logistic function analysis, which resulted in the removal of the following:

- Turbines of 200kW or greater within the first 200 unit deployments;
- Turbines of 300kW or greater within the first 1,000 unit deployments;
- Turbines of 650kW or greater within the first 2,000 unit deployments ;
- Turbines of 1MW or greater within the first 4,000 unit deployments.

The unit scale data is plotted graphically with respect to unit deployment number in Figure 4.9. According to the analysis carried out, 3,636 unit deployments consisting of unit capacities less than 620kW had taken place prior to the establishment of significant and continued unit-level up-scaling. By comparing this deployment with Figure 4.10, the formative phase took place over an 18-year period between 1977 and 1995. Additionally, the analysis suggested that industry-level up-scaling took place after the deployment of 3,362 units, occurring in 1994. Therefore industry-level up-scaling became established over 270 units (which were deployed over approximately one year) prior to the establishment of unit-level up-scaling, unique within the energy technologies considered thus far within this study. By observing the increase in the number of units deployed in Denmark over time, as shown in Figure 4.11, two distinct periods of growth can be seen. The first period occurred between 1981 and 1994. From 1996 to 2003, rapid increases in unit scale were being realised, and the level of industry growth accelerated concurrently. A period of four years followed in which very little new deployment was seen, which can be largely attributed to fluctuating policy support mechanisms creating uncertainties in the market (Meyer, 2007).

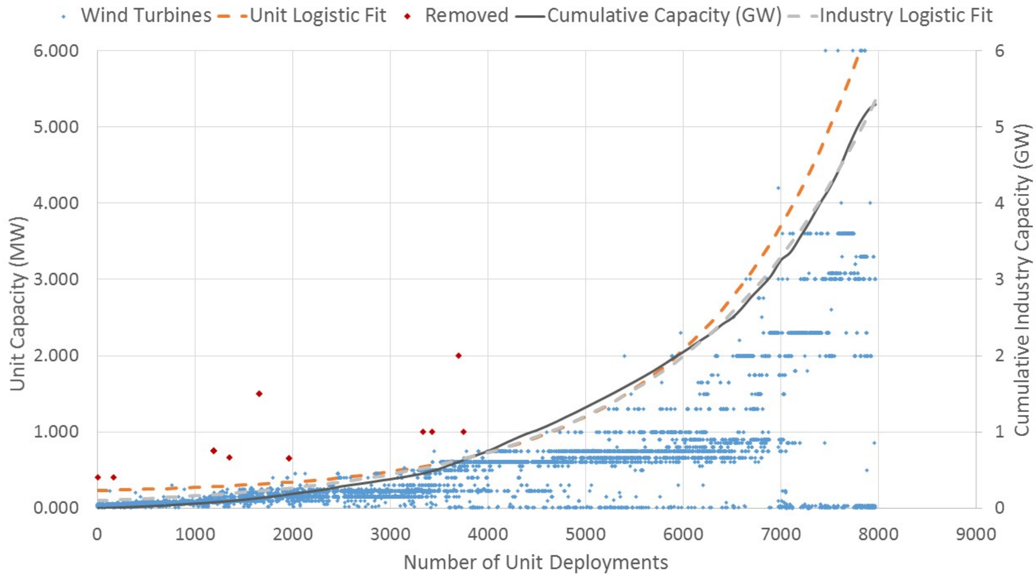

Figure 4.9: Danish onshore wind turbine unit deployment and logistic fit functions

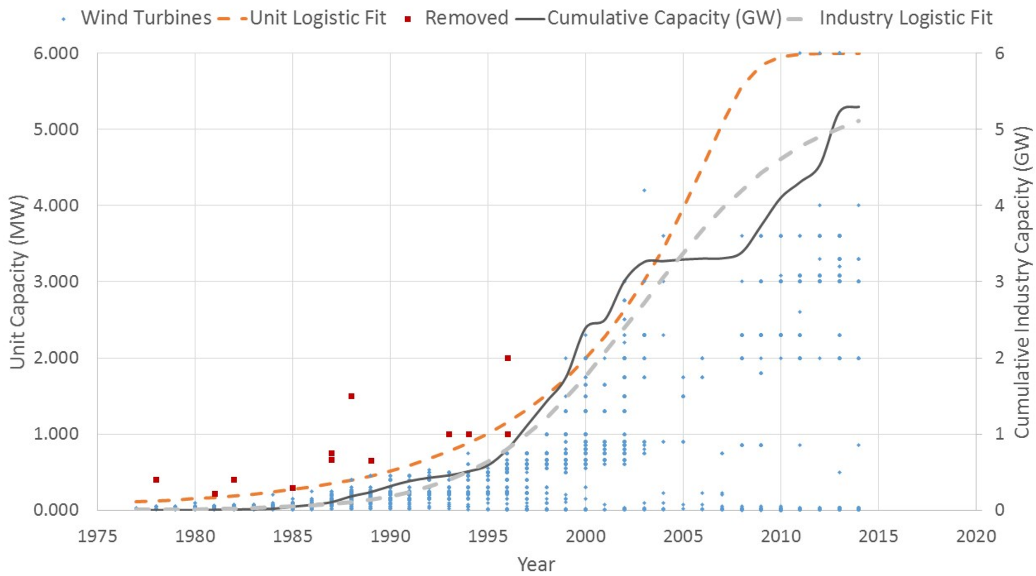

Figure 4.10: Danish onshore wind turbine unit deployment over time

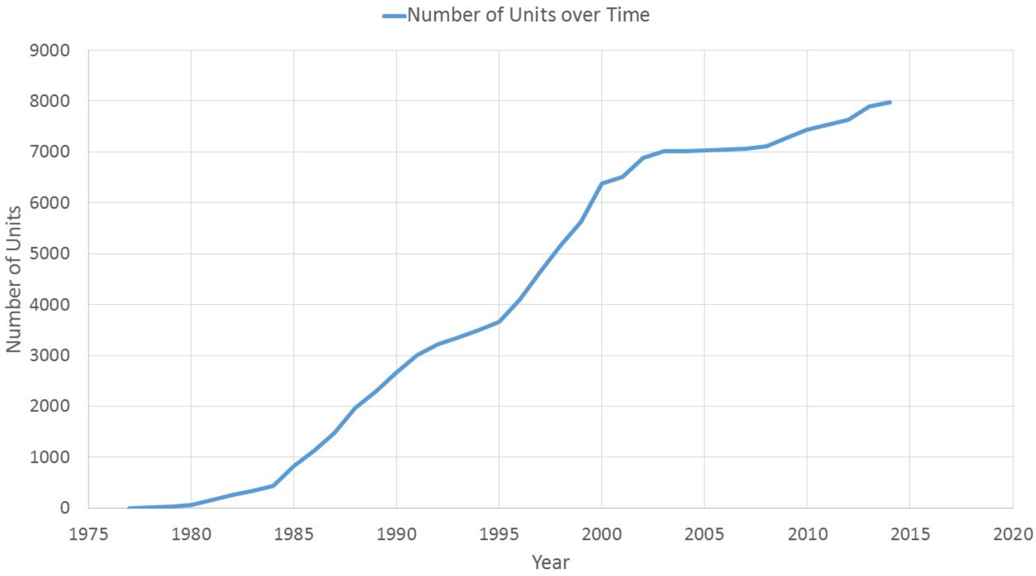

Figure 4.11: Danish onshore wind turbine number of units over time

4.3.4 Solar PV

Solar PV power stations consist of technologies that are modular in design and construction. Individual solar cells are combined to form PV 'modules' that are capable of large scale manufacture. A solar PV power station is achieved by incorporating large numbers of PV modules into array tables. Increasing the number of array tables (a mounting of multiple solar PV modules – see Figure 4.12) within a given solar array block allows for the realisation of larger peak power capacities (Wolfe, 2013).

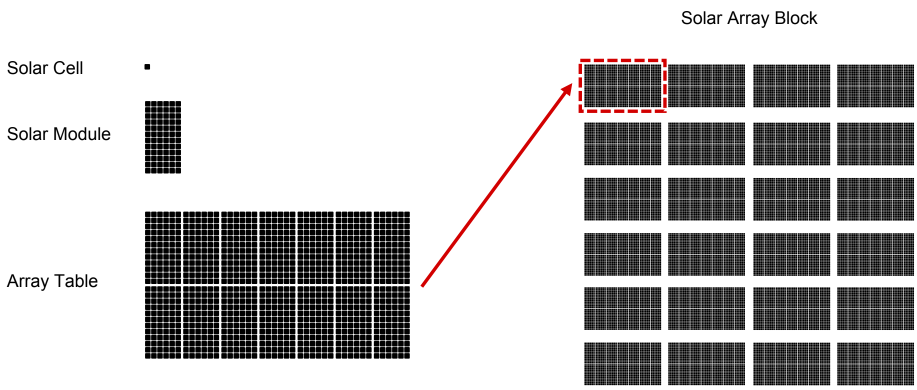

Figure 4.12: The modularity of PV components within a solar array

While individual PV modules vary in peak capacity depending on manufacturer and cell type used, a summary of the power output of modules used, the average module efficiency (based on the year of installation) and the number of modules used in certain reference PV power plant can be found in Figure 4.13.

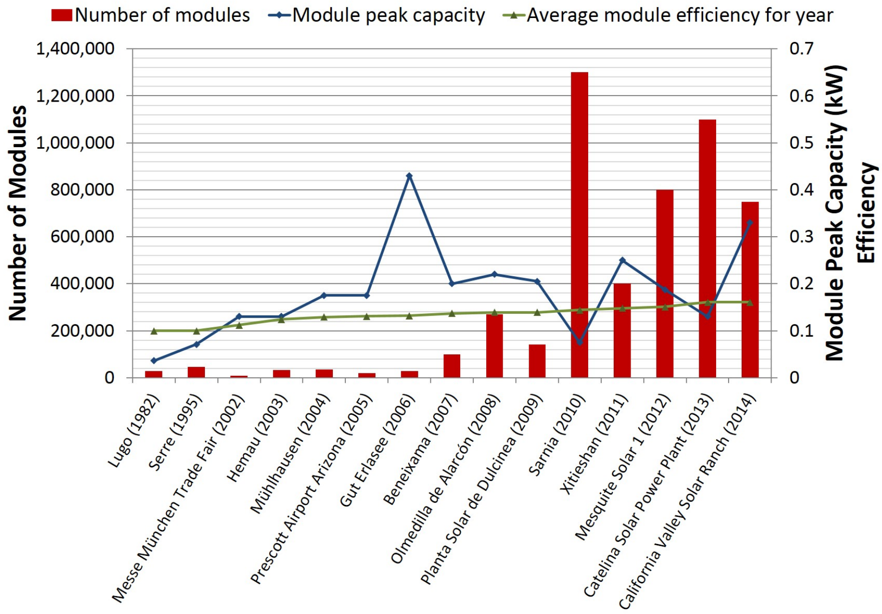

Figure 4.13: Module capacity, average efficiency and number of modules at selected sites

Figure 4.13 shows an initial general increasing trend of module peak capacity used in commercial solar array projects until 2006; subsequent large arrays utilise modules of more modest peak capacity, and there is no consensus in terms of optimal module capacity, with decisions being driven by CAPEX costs and revenue potential rather than being dominated by increasing unit capacities at a module level.

Increases in the efficiency of monocrystalline and polycrystalline C-Si solar cells has taken place incrementally, but steadily, over time, with the average efficiency across all types of monocrystalline C-Si solar modules entering the market reaching over 16% in 2013 (Siemer and Knoll, 2013). Module peak capacity can range from tens of Watts to over 800W.

From 2007 onwards, there is clear evidence of increasing numbers of modules utilised within the largest solar PV projects. While certainly there were still large numbers of PV arrays being constructed globally at more modest scale, the ability to build larger solar arrays increased substantially between 2007 and 2014. Although unit up-scaling took place at a module capacity level, increasing from approximately 40W in 1982 to almost 200W in 2004, the greatest up-scaling is seen at power plant scale (the number of modules used to reach the capacity for a given project).

Despite a rich history of research and development dating back to space applications in the 1950s, solar PV has only within the last decade started to see significant increases in global deployment for electrical power generation purposes. Large jumps in annual capacity additions took place during 2008 and 2010, predominantly due to increases in the European deployment led by the German market, and in 2011 through increased deployment in the Americas, Asia, and China (Aanesen *et al.*, 2012).

PV technology has demonstrated significant cost reduction through learning, and has been able to access the cost reduction opportunities in economies of scale, and unlock the levels of investment required in order to finance large scale construction projects at both manufacture and deployment level. The pace at which a PV power plant can be constructed is unmatchable through use of other technologies (Renewables Insight (RENI), 2012). As a result, solar PV technology is now capable of deployment in arrays hundreds of MW (in areas where a favourable resource exists) in relatively short timescales compared to other technologies within the power generation sector (Renewables Insight (RENI), 2012).

Data for solar PV technology within the US Energy Information Administration's Annual Electric Generator dataset considered total farm or array size, and not the unit scale of individual solar panels or modules (US Energy Information Administration, 2015). The dataset contained a number of outliers that impacted the fit of the logistic growth functions. Observation of this data suggested that these particular data points did not reflect successful growth when considering the remainder of the industry development and deployment trajectory. Additionally, the early large array deployments took place when the average deployment scale was still in the order of tens of megawatts. Subsequent deployment resulted in increasing average array capacity, however the early large array sizes were not replicated until a significantly larger number of unit deployments had taken place. The decision was made therefore to remove any data point from the analysis that consisted of an array capacity greater than or equal to 200MW prior to the 750th unit iteration. This resulted in the removal of 5 data points within an overall dataset consisting of 868 arrays.

Analysis of the data revealed that significant array level up-scaling did not become fully established until after 458 array deployments had taken place (see Figure 4.14). This formative phase developed over a 28-year period between 1984 and 2012 (see Figure 4.15). Observation of the data clearly shows that the formative stage of technology development was dominated by deployment of technology below that of the capacity limit, even before unit-level up-scaling became fully established. The rate of increase in array level up-scaling has not reached a point of inflection – as exponential growth is still being experienced within the solar PV sector.

At an industry level, significant up-scaling became fully established after the deployment of 420 array deployments, 38 units before the establishment of significant array-level up-scaling. Industry level growth is still being experienced, and no upper asymptote was apparent within the dataset. In a similar manner to wind energy, Solar PV experienced growth at an industry level slightly before array level growth.

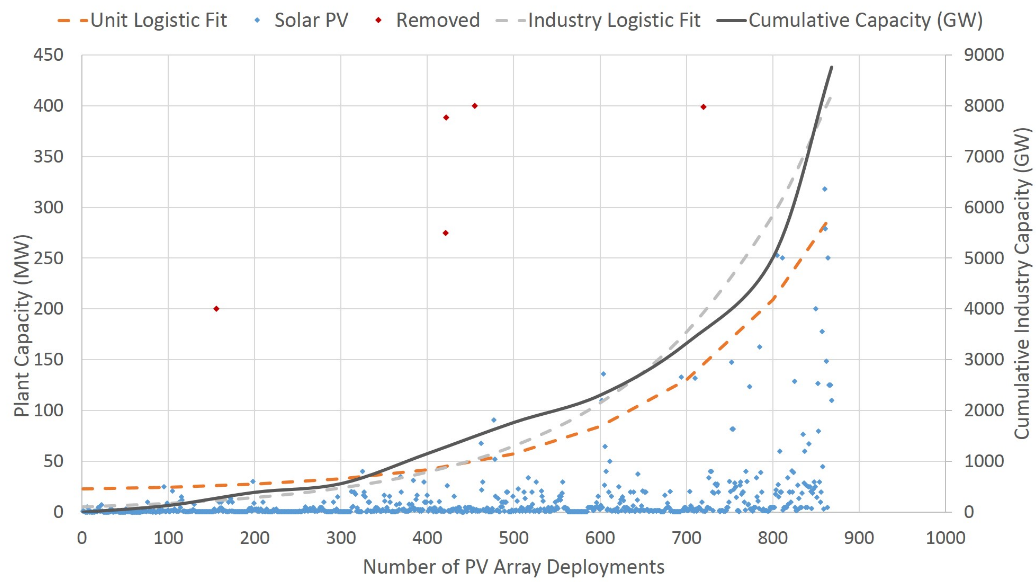

Figure 4.14: Solar PV array deployment and logistic fit functions

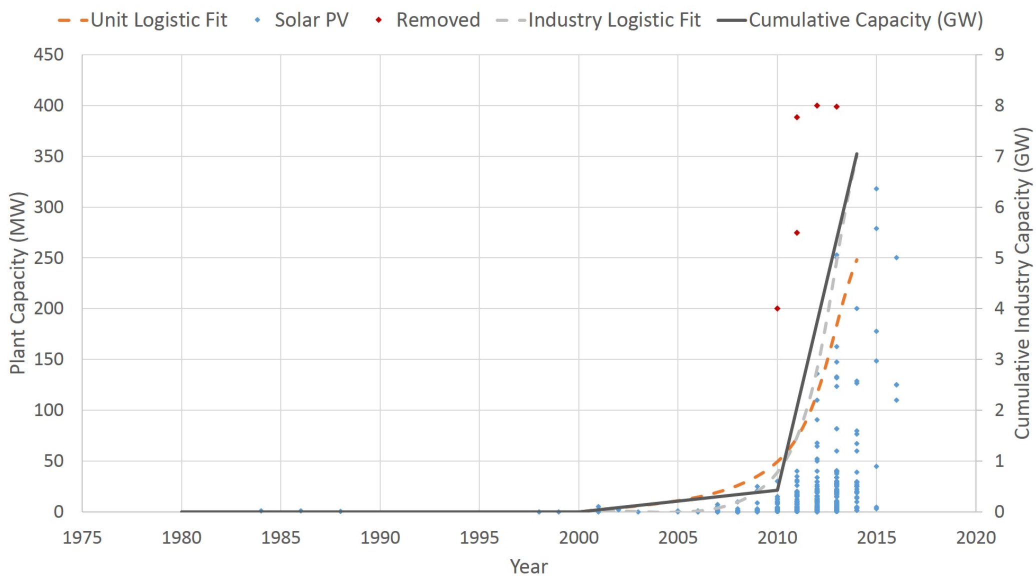

Figure 4.15: Solar PV array deployment over time

With regards to the number of solar PV arrays installed within the USA, after a small number of early innovators and pioneer array deployments, a solar boom took place from 2006, where rapid expansion in the number of solar PV array deployments occurred. This growth is shown in Figure 4.16. After a brief deceleration in deployment during 2008, exponential growth of array deployment occurred again until 2013. It should be noted that the rise in deployment of solar PV coincided with a sharp fall in the cost or solar PV – prices for solar PV plant have dropped by over 70% since 2006 (Solar Energy Industries Association, 2016) when the industry growth first experienced exponential growth.

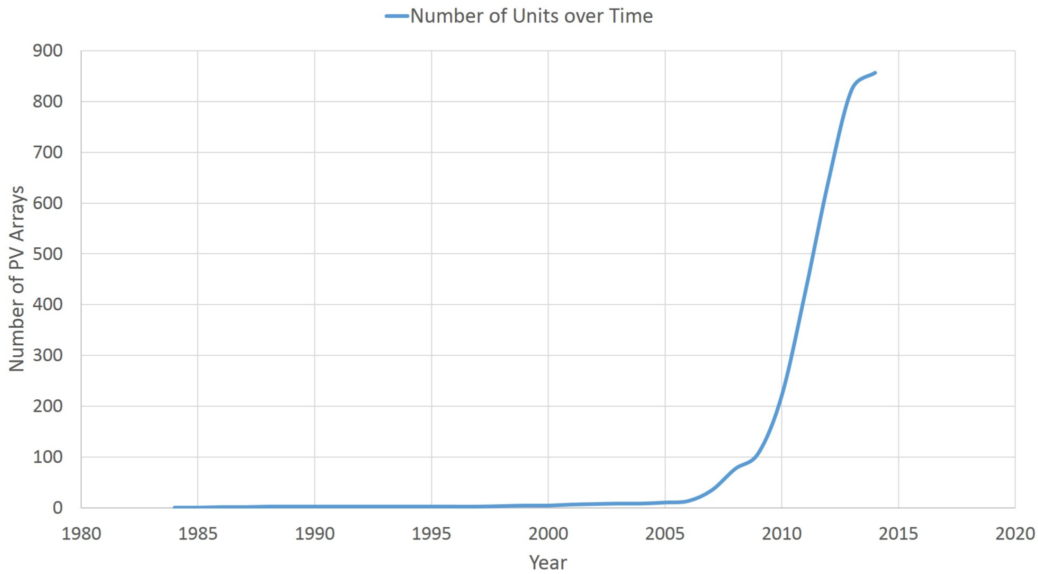

Figure 4.16: Solar PV number of arrays over time

4.3.5 Wave

Present day ocean energy philosophy appears to suggest that large megawatt-scale devices offer the best potential for the commercial success of the industry, as the majority of technology developers are focusing on large MW-scale machines. While utility companies and end-users could benefit from larger device capacities, and indeed many perceive that an economic case can only be made for large power outputs (Fraenkel, 2010), over aggressive up-scaling can be a major risk – particularly when a number of design iterations may be needed prior to the emergence of a truly reliable and de-risked technology.

Many of the leading government led marine energy incentives are now focused on deployment of large scale technologies in arrays that are several megawatts in size (Carbon Trust, 2014;

ADEME, 2015; European Commission, 2014b; The Scottish Government, 2014). For over a decade, the goal of the marine energy sector has been to create, and sustain, reliable and economic wave and tidal energy converters. However, to date, most examples of the technologies that have been developed for operation in a real-sea environment – aiming to provide consistent and reliable power output to the grid over long-term test periods – comes at a cost that is neither affordable (in comparison to alternative incumbent energy sources) nor sustainable for the long term (Ferro, 2006). In addition, ocean energy technology has yet to prove it is capable of reaching the desired level of system and sub-system reliability (Zhang *et al.*, 2009).

National and European level policies are providing significant levels of support for the nascent stages of the wave and tidal energy sector across European Member States, progress also is being made in countries further afield such as Canada and China (Zhang *et al.*, 2009; Mueller *et al.*, 2010; Wang *et al.*, 2011). However there is evidence of significant financial uncertainty amongst potential ocean energy investors and stakeholders (MacGillivray *et al.*, 2013a). There are still technical, political, and economic challenges facing ocean energy technologies, which will need to be overcome before commercialisation of the wave and tidal energy sectors can take place (Badcock-Broe *et al.*, 2014; MacGillivray *et al.*, 2013a; Ferro, 2006).

Large technologies designed for operation in the harsh marine environment involve significant quantities of steel, fabrication of mooring and foundation systems suitable for holding the technology in place, together with technology and components that can survive the rigours of a dynamic and powerful resource. All of these factors result in a significant increase in the financial cost of the prototype product. Given that these technologies are in the early stages of development, certain failures can (and should) be expected; reliability and availability of existing technologies offers significant room for improvement (Bahaj, 2011).

The data used within the study of wave energy technologies did not contain any data points that represent long-term installations, and all are pre-commercial prototypes with life-expectancy far shorter than the desired 20-year life of commercial products. It could therefore be considered that all points on the current wave energy logistic plot are, in fact, outliers – the units are not deployed permanently, and therefore the meaning is not equivalent to that in other technologies. The word 'demonstrated' has been used in place of 'deployed' to reflect this.

Whilst it is only possible to make a judgement on the likely maximum unit capacity value for a wave or tidal energy converter, the current maximum capacity of modular ocean energy technologies demonstrated to date is in the region of 2MW (EDF, 2015), but devices up to

11MW in scale have been proposed (Wave Dragon, 2005). However, wave energy devices in the region of 1MW in capacity have often been mooted as the optimal nominal unit capacity rating (de Andres, 2015), and research carried out for the EQUIMAR project claims that increasing the unit capacity of a WEC will result in decreased lifetime costs due to a reduction in installation and O&M costs per kW (Stallard *et al.*, 2016). Physical constraints that are present within the ocean energy sector characterise these limitations, such as the depth of water column – the distance between the sea bed and the water surface – and the physical mass required for structures to survive the intended loading regime as unit capacity (and therefore physical size) increases. Also, beyond certain sea conditions, ocean energy converters may be designed to enter a survivability mode, thus producing zero power output – analogous to wind turbines pitching out of the wind under high wind velocity storm conditions. Other research has suggested that WEC units should be designed with a maximum unit capacity of 300kW (Falnes and Hals, 2012), and the argument has been made that more appropriate development would utilise a larger number of small-scale devices in an array rather than a smaller number of large-scale devices (Falnes, 1994). However, unit deployments to date suggest that a focus on MW-scale technology is more prevalent.

Data for wave energy technologies demonstrated within UK waters, shown in Figure 4.17, reveals the rapid shift to large-scale technology at the outset of the industry's development. The unit-level growth rapidly increased following the first unit demonstration. Several unit iterations in the region of 700-900kW in scale have been demonstrated in the very early unit iterations, however subsequent industry growth through further demonstration of technology at this scale has not been achieved – there has not been utility-scale activity following on from the demonstration of pre-commercial prototypes. Moreover, the data points captured in this study represent a number of different concepts and technological solutions to wave energy conversion, and there is no convergence of design (unlike within other energy technologies).

When considering unit demonstration on a time axis, as shown in Figure 4.18, after the demonstration of a 75kW device in 2000, subsequent unit demonstrations until 2011 exceeded 300kW. Unlike other energy technologies explored within this section, wave energy did not experience learning from multiple unit demonstrations at a lower unit capacity before embarking on demonstration and deployment of large-scale devices. The data clearly shows that the formative phase has not taken place within the UK wave energy sector: data points are widely dispersed, there is no clear unit-level growth trajectory or opportunity for a stable and progressive future

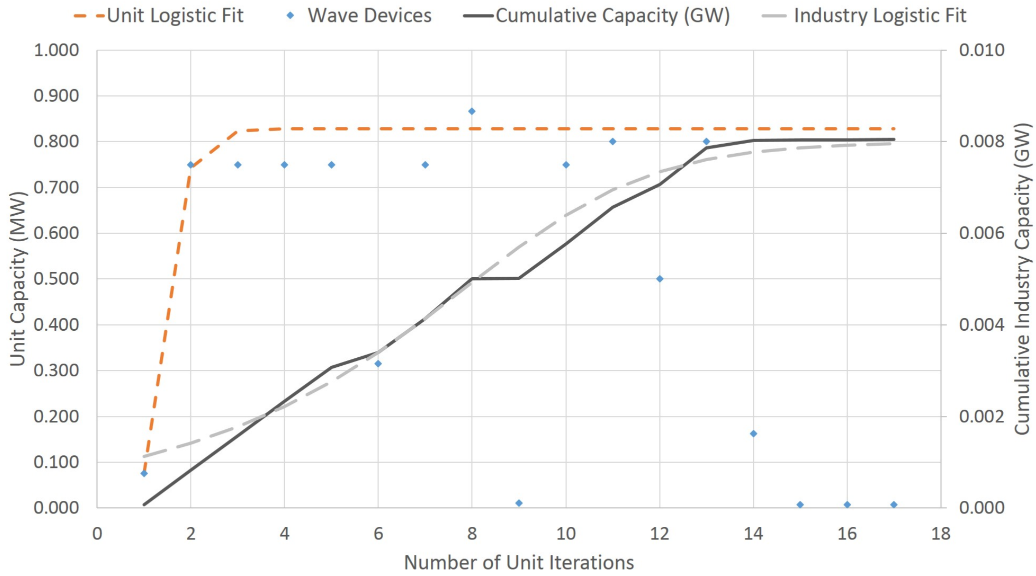

Figure 4.17: WEC unit deployment and logistic fit functions

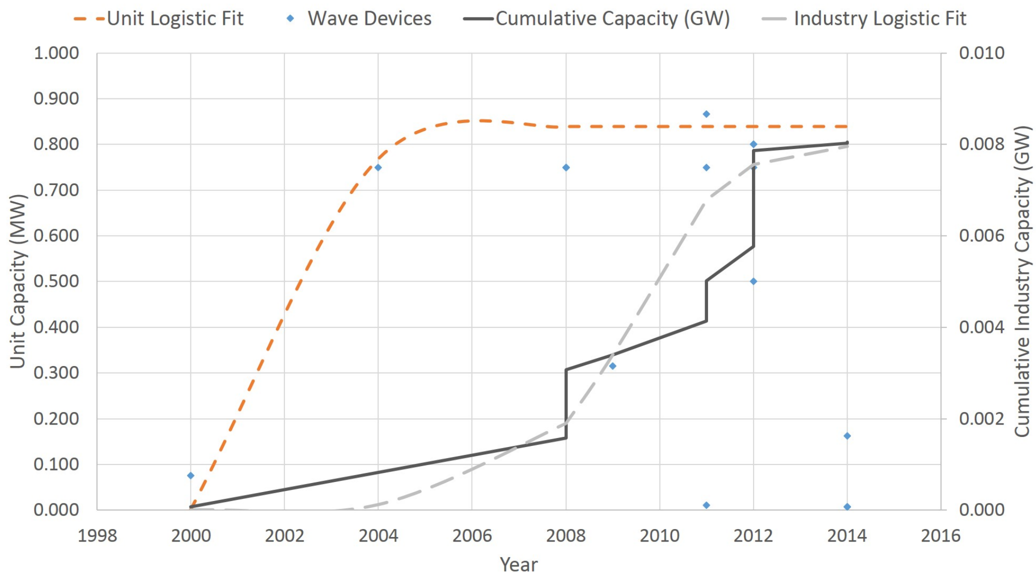

Figure 4.18: WEC unit deployment over time

unit-level growth, there is a fundamental limitation in the low number of data points, and there is no clear indication of the technology following an appropriate s-curve logistic function profile over a number of unit iterations as seen within successful energy sector technologies. There is a clear early push for "commercial utility scale" devices approaching 1MW in scale. Given that limiting unit capacities are likely to be in the region of those largest devices currently deployed, due to the economics of manufacturing the necessary structural components (French, 2006), the rapid progression to large scale technology prior to a formative phase of technology

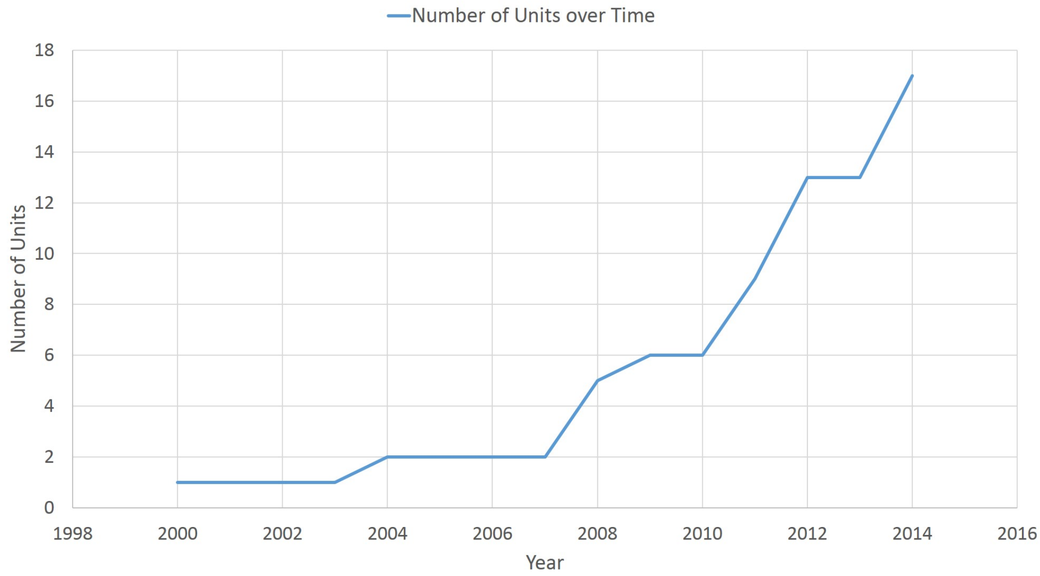

Figure 4.19: WEC number of units over time

proving has led to a lack of established data to benchmark unit growth, and a failure to iterate efficiently and cost-effectively. The levels of unit iteration are very low, but high expectations have been placed on the wave energy sector to date to deliver successful commercial scale power production. This growth pattern is in significant contrast to established energy technologies.

As shown in Figure 4.19, the level of unit demonstrations within the wave energy sector has remained modest over time, with the total number of UK demonstration units remaining below 20 units. No unit has yet achieved a full 20-year lifetime of operation, although this is still the goal of many technology developers. Of the units identified in Figure 4.19, none are currently operational in terms of actively generating power to the grid, and several of the developers behind the technologies have since entered into administration.

4.3.6 Tidal Stream

Despite a significant lack of deployment experience (in comparison to the wind industry), large rotors and large devices are the predominant technology of choice for tidal energy developers, as identified in Figure 4.20. This is reminiscent of the early government led wind energy research programmes of the 1980s (see Figure 4.7), which ultimately failed to develop a commercial wind turbine industry. The gradual up-scaling which took place during the formative stages of commercial wind turbine development appears to be omitted completely within the tidal energy sector for a large number of technology developers. It should be noted, however, that the two devices with confirmed sale and installation in an operational environment (therefore considered to be commercial turbines) are small diameter turbines.

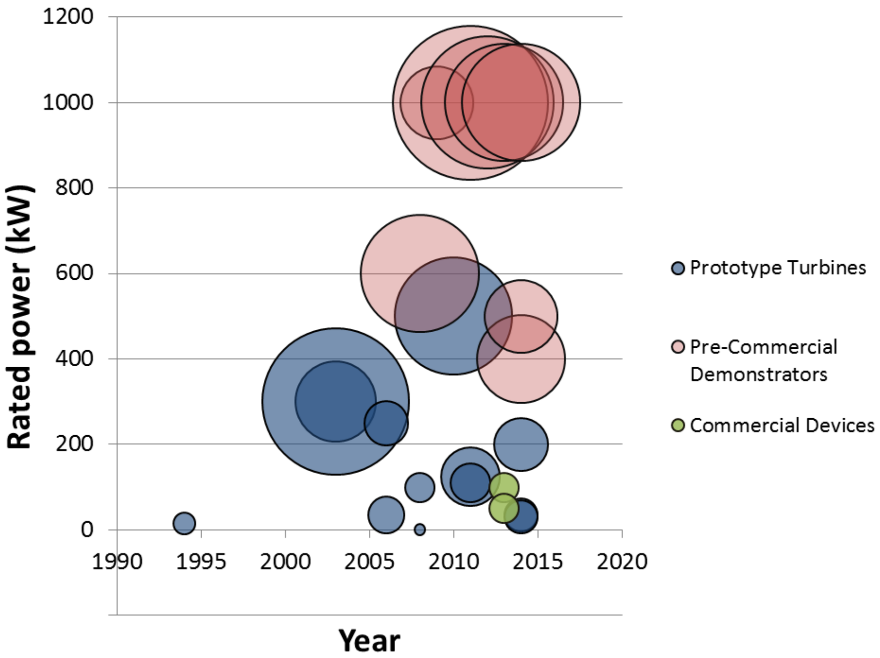

Figure 4.20: Horizontal axis tidal turbine rotor development – early convergence around MW-class technology

Within the tidal energy sector, some early prototype demonstration did take place using turbines considered to be small-scale (the order of tens of kW). The small number of data points do reveal a rapid progression to MW-scale technology in a similar manner to the wave energy sector, as shown in Figure 4.21. Data from UK based deployments suggest that unit-level up-scaling took place instantly after the first deployment, and rapidly reached an asymptote of 1MW by the time the 10^{th} unit had been deployed.

Considering demonstration on a time-axis, the up-scaling phase occurred rapidly between 2004 and 2010 (see Figure 4.22). Although there are a number of deployments that continue to take place at kW-scale, there is clear evidence to suggest that the formative phase of technology development has again been omitted, which contrasts heavily with all but the wave energy example. Data points are widely dispersed, there is no clear unit-level growth trajectory or opportunity for a stable and progressive future unit-level growth, there is a fundamental limitation in the low number of data points, and there is no clear indication of the technology following an appropriate s-curve logistic function profile over a number of unit iterations.

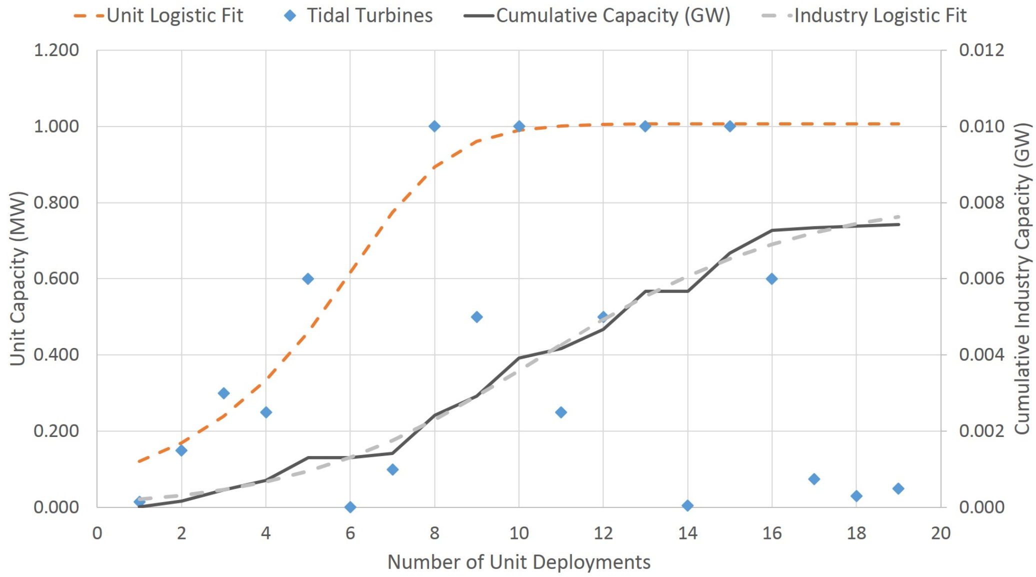

Figure 4.21: TEC unit deployment and logistic fit functions

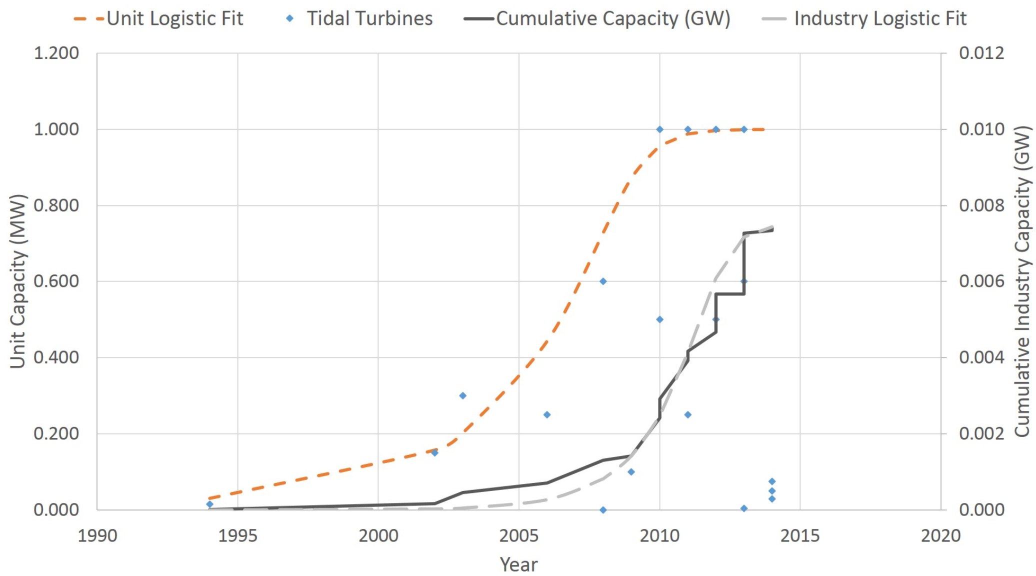

Figure 4.22: TEC unit deployment over time

As shown in Figure 4.23, the level of unit demonstrations within the tidal energy sector has remained modest over time but has continued to steadily grow. The total number of UK demonstration units remains below 20. No unit has yet achieved a full 20-year lifetime of operation, although it should be noted that one UK-based deployment achieved 8 years of operation before being decommissioned. Of the units identified in Figure 4.23, very few are currently operational, and, as with wave energy technology, several of the developers behind the technologies have since entered into administration.

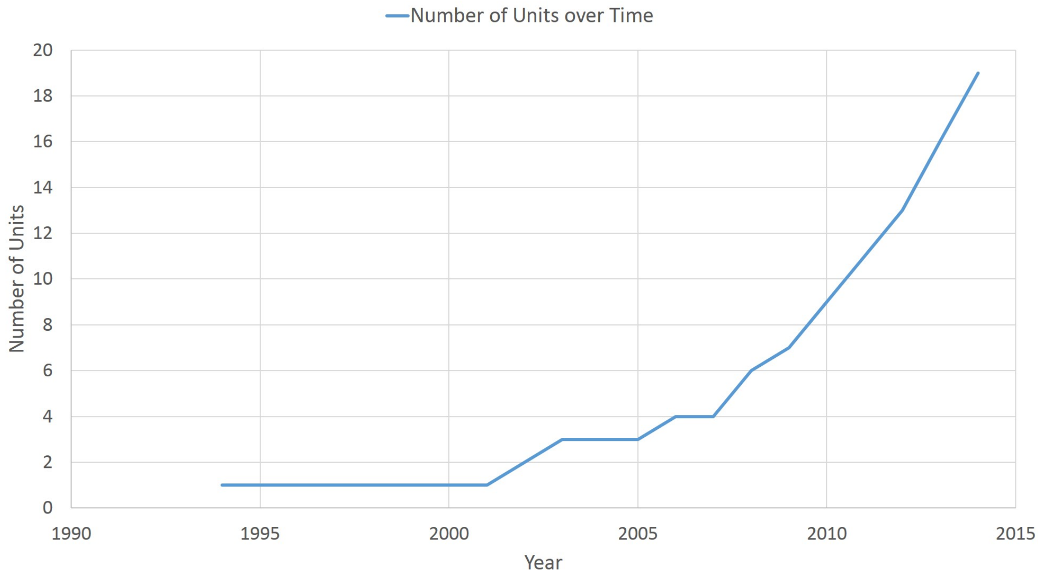

Figure 4.23: TEC number of units over time

There has been little evidence to suggest that the technology has given the required confidence to investors that will justify the level of investment that is needed to sustain continued development at larger technology scales (MacGillivray *et al.*, 2013a).

It should also be noted that further UK deployments have been consented, utilising tidal turbine technology with a capacity of 1.5MW per device (MeyGen, 2015). Tidal turbines to be deployed further afield in France and Canada have rated capacities of 2MW per device (DCNS Open Hydro, 2015), however, the power output from a single rotor is unlikely to increase beyond this level. For example, the rotor of a tidal turbine will be limited by the depth of the water column due to the desire to avoid the large shear profile at the sea bed, and wave interaction and transport shipping draft close to the surface. Deployment of technology greater than 1MW represents further unit level up-scaling without significant deployment at earlier technology scales – continuing to follow the trend of up-scaling prior to successful emergence from a formative phase.

Whilst the data for wave and tidal stream energy technologies consists of only a few data points, there is a clear and stark difference in trend between the ocean energy technologies, and the historic growth pathways followed within other mature and established energy sector technologies.

The majority of wave and tidal energy device developers are using MW-scale devices as a proving ground for technology and performance validation (SI Ocean, 2012). It was perceived by the early wave and tidal energy sectors that future customers, such as utilities, would purchase turnkey farms or arrays of devices, but the development costs of the technology falls primarily in the hands of the small to medium enterprises (SMEs).

This places a large financial burden on companies who may only have limited capital expenditure capabilities, and rely principally on government or private sector funding. A substantial investment is required to reach the MW sized 'full-scale' pre commercial milestone under the existing development environment – in the order of £120 million (Weber, 2012) – with the Carbon Trust stating that pre-commercial demonstration units can cost in the region of £10-30 million (Carbon Trust, 2011). It is significantly harder to raise capital to incrementally innovate when even a small iteration to a device could cost in the order of several million pounds – this model does not facilitate an economically attractive technology proving or 'formative' phase.

While there are some distinct similarities between wind energy converters and tidal stream energy converters, wave energy technology is a very novel and new application with very little transferability from the wind energy sector. However, wave energy device developers are still focusing efforts on the deployment of large MW-scale technologies, even with a lack of knowledge transfer and understanding from other sectors.

The perceived next step in the development process for MW-scale wave and tidal energy technologies, array deployment, requires the investment in the order of €70-100 million for the first 10MW arrays to finance the capital intensive first arrays of wave and tidal energy converters (Badcock-Broe *et al.*, 2014). While costs are anticipated to reduce in the longer term (in line with increasing levels of deployment and larger production levels leading to economies of scale) (Mueller and Wallace, 2008; Gross *et al.*, 2003), the early array projects under development, such as those targeted by European NER300 funding, are struggling to reach financial close (Badcock-Broe *et al.*, 2014). Locked in to large scale (and therefore large cost) technologies, developers are struggling to raise the capital needed in order to progress the sector beyond the device demonstration phase.

4.3.7 Summary of Data

The key logistic function parameters for steam turbines, gas turbines, and wind turbines that were developed within this study are identified and presented in at both unit level and industry level in Tables 4.3 and 4.4 respectively. These tables contain the necessary parameters that will allow the recreation of the 5PL functions that have been developed within this work.

Wave and tidal energy technologies have not been included in these tables, as technology has been demonstrated rather than deployed (full commercial project design life has not been met in any case). The 'Initial' column represents the unit capacity of the first unit, in MW, or the cumulative (industry-level) deployed capacity prior to the first unit deployment, in GW. The 'Cap. x_i' column represents the unit or industry level capacity at the point at which up-scaling is initiated (x_i), in MW (unit level) or GW (industry level). It should be noted that the parameter T for gas turbines at an industry level, and the renewable energy technologies at both unit and industry level represent future estimates based upon parameters of the solved fitted logistic function, and should not as such be taken as future projections – these parameters are necessary in order to recreate the relevant logistic functions that fit the growth up until the current deployment, and should only be used to consider the historic deployment and not to make future projections. Additionally, the x_{mid} parameter for the renewable energy technologies also represents a future estimate based on the solved logistic function, and are not projections of future deployment.

Technology	Initial Capacity (MW)	Capacity at x_i (MW)	B (MW)	T (MW)	x_i (units)	x_{mid} (units)	x_f (units)	b	s	R^2
Steam Turbines	0.0075	188	48	1450	799	1543	2491	0.00108	1.16000	0.992
Gas Turbines	24	49	29	232	759	1994	2458	0.00146	0.55236	0.989
Wind Turbines	0.022	0.62	0.19	10	3636	8689	NA	0.02811	0.00962	0.982
Solar PV	1	50	20	NA	460	1427	NA	0.10358	0.02275	0.945

Table 4.3: Summary variables for calculated 5 parameter logistic growth functions for unit level growth

Technology	Initial Capacity (GW)	Capacity at x_i (GW)	B (GW)	T (GW)	x_i (units)	x_{mid} (units)	x_f (units)	b	s	R^2
Steam Turbines	0	62	0	621	1233	2639	3027	0.00153	0.46000	0.999
Gas Turbines	0	33	0	325	887	1623	NA	0.00033	2.85523	0.998
Wind Turbines	0	0.53	0	13.9	3362	9866	NA	0.00102	0.21511	0.997
Solar PV	0	0.876	0	NA	420	1067	NA	0.01697	0.12784	0.979

Table 4.4: Summary variables for calculated 5PL growth functions for industry level growth

4.4 Technology Conclusion

This section has investigated the development trajectory of several technologies, both renewable and non-renewable in nature. There is a clear pattern of evolution within successful innovation and diffusion: prior to widespread adoption of an energy technology, or indeed unit capacity up-scaling, a 'formative' period of development must take place. The research suggests that large numbers of device deployments over a longer-term time-frame, demonstrating significant levels of reliable operation, often using small-scale technologies (in comparison to the eventual product scale upon reaching the industry growth phase), are pivotal in the formative phase of technology development.

It is clear to see that the historic development trajectories of existing power generation technologies has followed a gradual unit-level up-scaling process, over the course of many unit iterations. However, the early wave and tidal energy sector appears to be attempting to bypass this early formative phase altogether. Technology developers within the ocean energy sector are attempting to develop arrays prior to optimising a cost-effective and reliable single unit. Wave and tidal energy technologies are attempting to go big before they have successfully proven at small scale. There is evidence to suggest that the ability to iterate and successfully commercialise technology comes after a long period of formation – something which many wave and tidal energy technologies are attempting to bypass.

4.5 Note on Scaling

A point of caution to be noted is the different opportunities to scaling that exist within wave and tidal energy technologies. While small scale tidal energy converters can be placed within flows of equal velocity to that targeted by large scale technologies, making the deployment of small scale technology a more trivial issue by comparison, the complexities of the wave energy resource mean that the resource must be scaled appropriately with the device to ensure survivability. The desired resource characteristics need to scale appropriately with the device. Wavelengths would be scaled linearly with the device scaling factor (SF), while wave period would be scaled to the power of 0.5 with respect to the device SF (Holmes, 2009). Tidal energy has an advantage over wave energy in this respect.

The power output of tidal energy converters scales to the power of 2 with respect to the SF, due to the relationship between power output and swept area of the rotor (i.e. SF^2); for wave energy converters the power output scales to the power of 3.5 with respect to the SF (i.e. $SF^{3.5}$) (Holmes, 2009).

For example, a tidal energy converter four times the size of an original would be expected to have a power output 4^2 (sixteen) times greater than the original power output; a wave energy converter four times the size of an original would be expected to have a power output $4^3.5$ (128) times greater than the original power output. The inverse would be true when reducing the unit-scale, and therefore small scale wave energy technologies for energy production may not be an attractive long-term prospect. However, the argument this chapter makes is that the support of small-scale technology development within a formative phase is necessary in order to facilitate the learning and knowledge that will filter into subsequent up-scaling and commercial iterations of technology.

Chapter 5

Economic Analysis and Application of Learning Theory

5.1 Chapter Introduction

This chapter presents an analysis of learning curves and their application in the wave and tidal energy sector, and presents the investigation of the impact of minor perturbations in input parameters on learning curve trajectories using a cost model created as part of this research.

The cost model and wider economic analysis within this chapter considers only CAPEX costs. The justification for this is that, while OPEX costs will have a dramatic impact on the overall lifecycle costs of a technology, OPEX costs are deeply uncertain at this stage in technology development, and it is the CAPEX costs that have the most significant impact on the repeatability, the cost of iteration, and the ability to iterate rapidly whilst in a formative stage of development. While in a pre-commercial stage of development, neither CAPEX or OPEX costs will be competitive with other technology solutions, but it is hypothesised that the ability to maximise the number of iterations within a given CAPEX cost may prove critical in successfully navigating through a formative stage of development, allowing engineering improvements and technology advancement, hence the omission of OPEX within this chapter.

The limitations of this approach would be most significantly apparent in the wider commercialisation and roll out of technology once beyond a formative phase of development. When commercially driven projects require lifecycle costs and revenues to be predicted in greater levels of detail, OPEX costs, based on operational experience, will play a dominant role in the attractiveness of a particular technology. The applicability of the approach within this chapter is therefore limited to pre-commercial technology development, demonstration and deployment within a formative phase of technology development. A second limitation of a CAPEX only approach is the bias that results from the removal of OPEX costs from a project with regards to unit scale. One of the advantages of technology up-scaling is the reduction in OPEX costs on a cost-per-kW basis. This advantage is ignored within the CAPEX only study, and limits the applicability of the approach used herein once a mature technology with long term operational performance has been demonstrated and OPEX has been proven.

The conclusions drawn within this chapter are therefore representative of a formative phase of development only, and may not be appropriate for longer-term industry projections beyond the formative phase.

5.2 Cost Reduction – Learning Theory and Learning Investment

Learning rates and learning curves have been suggested as suitable tools for application in the analysis of the overall investment requirements in bringing a new technology to commercialisation. Of particular interest in the context of this thesis is the learning investment, the investment required for deployment of a new – and more costly – technology over and above the cost of deploying an already cost-efficient alternative. In order to gain a greater understanding of the economic implications of the uncertainties that currently exist in the ocean energy sector – for example, investigation as to whether the current trajectory is affordable, and the implications of small changes to the input parameters on overall development and commercialisation costs – Learning Theory will be investigated. Of particular interest is the need for ocean energy to reach cost competitiveness with technology that is currently competing for investment and government support in a similar context: offshore wind. Specific functions and mathematical formula are discussed within Chapter 3 (see Equations 3.3 and 3.4).

The historic effects of learning by doing are clear – indeed several energy technologies have achieved fuel parity (competitiveness with fuel costs in remote locations where stand-alone diesel generators are the primary source of electrical power) and may be close to achieving grid parity (competitiveness with electrical power generation at a utility level) despite having started from a far high-cost baseline (Bhandari and Stadler, 2009; Breyer and Gerlach, 2013; Breyer *et al.*, 2010).

There is, however, a danger in applying similar phenomena to future projections for novel technologies, as it is impossible to accurately predict the future learning rate or number of units deployed before substantial cost reduction will take place. For example, offshore wind turbine technology has failed to realise significant or sustained cost reduction despite over 1GW of deployment (see Figure 3.5), despite much industry prediction of immediate cost reductions. There is a danger that wave and tidal energy technologies, banking on early and sustained cost reductions to make an attractive investment case, could be exposed to similar challenges.

The objective of the economic analysis is to explicitly identify the impact of small perturbations to model input parameters on the assumed learning curve trajectory. This would, in turn, impact the learning investment requirements for bringing new technologies to a level of cost-competitiveness with a desired target.

As has been discussed within Chapter 3, learning curves are often used as an analytical tool for technology forecasting. However, this process involves making assumptions over a wide number of uncertainties, often implicitly within the calculation.

Although seemingly simplistic in approach, the use of a single factor learning rate model is an appropriate means of determining the range of plausible learning investments required in order to allow ocean energy technologies to reach a level of cost-competitiveness with a 'benchmark' technology. In the case of this research, the technology benchmark is assumed to be offshore wind turbines, technology that itself is in need of substantial cost-reduction, but can be considered as a 'competitor' technology to those of wave and tidal energy in terms of its need for government incentive mechanisms and large scale private sector investment to support deployment.

If ocean energy cannot compete with offshore wind in the longer term, then the investment focus will inevitably be the technology that offers greatest security and largest return on investment. In the medium term, ocean energy technologies will need to demonstrate significant cost reduction on a trajectory towards offshore wind costs if a commercial industry is to be sustained for the long-term. This research will consider the economic uncertainty surrounding deviation from optimistic development trajectories presented in industry reports. The analysis that is to be reported in within this chapter highlights the sensitivity of ocean energy learning investment to three parameters:

1. SC: The capital cost of the first devices ($C(x_0)$ Equation 3.3);
2. CSCR: The level of cumulative deployment (in terms of the number of devices) prior to the emergence of sustained and continuous cost reduction (x_0 in the above equations); and
3. LR: The average rate of cost reduction with each doubling of deployment.

The input parameters are explained in Figure 5.1, with the learning rate defining the steepness of the cost reduction trajectory. The learning curves presented in this work are therefore synthesised to represent simplified plausible cost reduction trajectories.

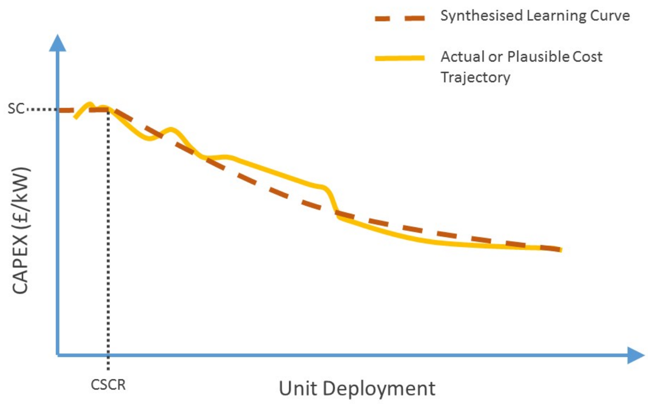

Figure 5.1: The Learning Trajectory Assumption

The favourable selection of input parameter values for a cost reduction and learning model can be seen to represent very attractive scenarios, particularly in terms of the overall level of investment required for ocean energy to reach cost-competitiveness with offshore wind.

The best available data on ocean energy starting costs and learning rates (metrics conventionally used for learning rate analysis) are found in the literature (SI Ocean, 2013; Carbon Trust, 2011; Low Carbon Innovation Coordination Group, 2012), and were considered within industry engagement within Chapter 2.

The deployment level at which sustained cost reduction will occur is impossible to predict accurately, therefore a range of plausible assumptions have been presented for this variable based on analysis of what has been achieved within historic energy sector technologies. Sustained cost reduction is generally achieved after technology shakeout phase, whereby convergence upon optimal design concepts emerges. A sensitivity analysis was carried out with the following parameter perturbations:

1. SC was varied at 100 £/kW increments, from a reference of 6,000 £/kW, between 3,000 £/kW and 10,000 £/kW (with reference costing consistent with that used in the literature

(MacGillivray *et al.*, 2014; SI Ocean, 2013));

2. The assumed LR was a reference of 12%, with high and low scenarios of 15% and 9% respectively, based on Carbon Trust (2011). An additional scenario of 18% was included as higher learning rates could plausibly be seen in early technology development of high cost equipment;
3. CSCR was varied at increments of 10 devices, from a reference of 20 devices, between 10 and 500 devices. This range encompasses the optimistic deployment scenarios anticipated within ocean energy reports, and plausible scenarios whereby cost reduction is not easily attained at an early stage – although still occurring earlier than was the case for offshore wind.

It should be noted that the reference case utilised for this work does not represent a mid-range point of the uncertainty ranges, nor does it represent the most likely cost reduction trajectory. Rather, it encodes high-end assumptions of the rate of cost reduction, and low-end assumptions of initial CAPEX and deployment before sustained cost reduction, representing an attractive view on the future development of the wave and tidal energy sector – one which has largely been adopted within the industry itself as its most likely trajectory, but is unlikely to be realised in the short-term, given the current project costs for pioneering projects (MeyGen, 2015).

Several assumptions were made to enable this study:

- The cost sensitivity is based on total capital cost (CAPEX), rather than the total cost of energy supplied (the 'Levelised Cost Of Energy', LCOE). While a CAPEX-only learning curve analysis is common for emerging technology analysis (Junginger *et al.*, 2010a), and accounts for a major proportion of the LCOE for offshore energy technologies (Carbon Trust, 2011), a LCOE-based analysis would require detailed assumptions about device availability, OPEX and project site specific resource analysis, some of which are deeply uncertain at this stage. For analysis of the LCOE for marine energy, see Ocean Energy Systems (2015), Carbon Trust (2011), Allan *et al.* (2008) and de Andres *et al.* (2014);
- The generic marine device technology unit analysed here was initially assumed as a 1MW rated device, such that deployed capacity in MW and number of devices constructed are identical;

- Offshore wind farm CAPEX costs are taken to be 2,800 £/kW, reflecting cost estimates from industry data (4C Offshore, 2012), and is thus used as the target cost for ocean energy technologies;

A cost reduction model was developed, discussed in detail within Section 5.5. This allowed multiple cost reduction trajectories to be generated as an output of the model – an individual learning curve for each plausible combination of input parameters. For each specific learning curve, the unit investment requirements were calculated by multiplying the CAPEX cost (in terms of £/kW) at each unit deployment by the assumed capacity of the device. This was repeated for each unit deployment until cost competitiveness with the target was reached. The total investment is the sum of all individual unit deployments, equivalent to the area underneath the learning curve. The cumulative capacity of deployment was calculated by multiplying the number of deployments to reach cost competitiveness by the assumed device unit capacity.

The cost of deploying an identical capacity of offshore wind was calculated by multiplying the above cumulative deployed capacity by the current cost of offshore wind, 2,800 £/kW. The learning investment is then calculated by subtracting the equivalent offshore wind deployment cost from the investment cost for marine energy deployment. Through investigation and comparison of scenarios, the affordability of, and variation between, overall learning investment requirements can be analytically presented and discussed.

In addition, it was expected that this analysis would provide an assessment as to whether the uncertainties inherent in assumptions used within the wave and tidal energy industries are realistic in terms of levels of risk for stakeholders and investors within ocean energy technologies – ultimately addressing whether the current research, development and innovation environment within wave and tidal energy technology formative phase development can be fully expected to deliver successful technology commercialisation in an economically sustainable manner.

5.3 Learning

Technological advancement and the successful diffusion of complex engineering systems into societal use are the result of intricate navigation through a series of interlinked challenges within political, economic, technological and social circles (Hughes, 1983).

In the emerging wave and tidal energy sectors, the development of engineering progress has been impacted greatly by factors external to the technological development itself. The strategic development of ocean energy requires knowledge of the technology itself, but also the wider network of complex interaction in which the other factors can dictate or dominate research, development and innovation pathways.

A combination of policy and funding mechanism guidelines and requirements, utility desire for levels of power generation commensurate with that of more mature renewable energy technologies such as wind, and over-optimism with regards to the development timescales for wave and tidal energy technologies gave impetus for a rapid transition to large-scale technology deployment within the wave and tidal energy sector.

As this research has already pointed out, there is a drive for commercial application of technology prior to successful emergence from a formative phase of technology development. Certain ocean energy technology has, to an extent, been demonstrated to be feasible, and shown to be capable of generating electricity over short-term to medium-term periods of time. This has been at a significant capital cost, with frequent challenging and costly maintenance procedures, and with very little deployment beyond pre-commercial demonstration. As such, the cost of demonstration has proven to be largely impractical for multiple unit deployment under the support of private sector investment, and reliance on government and public sector support mechanisms is essential in order to facilitate the demonstration of subsequent technology iterations.

Interest and support for the wave and tidal energy sector is predicated on rapid and sustained cost reduction. While there is recognition that the early cost of deployment is high, and that prototype costs do not reflect the likely costs of commercial units, there is a challenge ahead for ocean energy technologies to achieve the necessary cost reductions in order to make them economically attractive to future investors.

However, when considering implementation of technologies that have not yet reached full commercial maturity, there is a risk that the assumptions inherent in any economic appraisals or cost projections could be more optimistic than the eventual reality. This has proved to be the case within the offshore wind energy sector, which, despite early cost reduction projections, saw cost *increases*, largely due to ‘under-design’ by taking land-based wind turbine solutions offshore.

Learning, a phenomenon well documented in the literature, is a function of unit deployment (MacGillivray *et al.*, 2014; Junginger *et al.*, 2010a; Neij *et al.*, 2003; Rubin *et al.*, 2015). There exists very little published research on learning rates specific to marine energy within academic literature, due to limited cost data available, but some industry reference reports consider future costs of wave and tidal energy technology based upon industry engagement (Carbon Trust, 2011; Callaghan and Boud, 2006; Allan *et al.*, 2008). The available work carried out in industry reports tend to use single factor experience curves. In these, the technology cost at a given point is calculated as a function of cumulative experience, or GW deployed.

Without significant physical deployment to provide evidence for cost reduction, ‘learning by doing’ within the wave and tidal energy sectors is restricted to theoretical analysis, making assumptions on future trajectories (MacGillivray *et al.*, 2014; SI Ocean, 2013). The analysis of cost reduction and learning used in this section therefore utilises a combination of expert judgement underpinning the UK marine energy sector roadmap (Energy Technologies Institute, 2014) with published studies of marine energy cost forecasting using learning rates and bottom-up reference engineering studies (Carbon Trust, 2011; SI Ocean, 2013; Low Carbon Innovation Coordination Group, 2012).

The single factor learning curves in historic work fail to account for the uncertainty inherent within any forecasting process, particularly when estimated costs are based upon expectations within the wave and tidal energy sectors, often without external validation. The aim of this chapter is to explicitly consider the impact of uncertainties on the learning and cost reduction process, and to present the results of a sensitivity analysis that was carried out within this research.

Historic examples of learning rates found in selected energy technologies are presented in Figure 3.5, which leads to the expectation that wave and tidal energy technologies could achieve similar cost reduction trajectories. As has been found in other industries to date, fluctuating costs, and periods of cost increase can be experienced in the early stages of technology development. Offshore wind technology (between 2002 and 2007) and Gas Turbine Combined Cycle technology (between 1975 and 1990) saw periods of cost increase. Perhaps most pertinent to this research is the trajectory followed by offshore wind. At a European level, the capital costs of offshore wind vary by country, influenced by geographic variations in bathymetry, sea bed substrate type, and distance to shore, but the cost of turbines and components has also been subject to fluctuations in commodity prices (Greenacre *et al.*, 2010).

Even in technologies where cost reduction is apparent, sustained cost reduction does not usually initiate at the initial outset of development. While some cost reduction is perhaps achieved in early stages of development, the price of technology (paid by a customer) may initially be lower than the cost of development. With experience gained by learning-by-doing and learning-by-using, in conjunction with product and production standardisation, and unit deployment and up-scaling, the costs are likely to decrease. However, the price to the customer may not reduce at this point – this stage is considered as a price umbrella (Boston Consulting Group, 1968). At a certain stage in the technological development within a sector, smaller companies may be acquired by larger firms as technology consolidates around the strongest design and others may leave the market altogether. These processes result in what is known as ‘shakeout’. With competition between dominant players, the price of the technology is more likely to closely follow the cost, as indicated in Figure 5.2 (Boston Consulting Group, 1968).

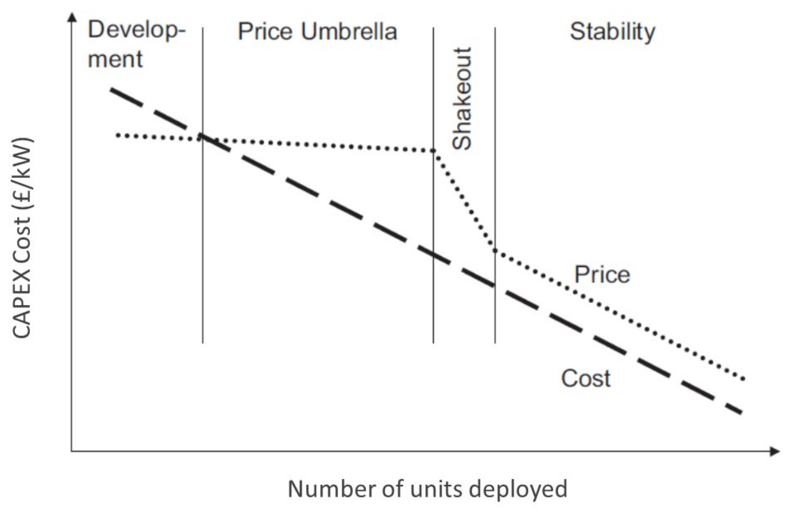

Figure 5.2: Price-Cost relation for a new product (Boston Consulting Group, 1968)

The cost of Danish wind turbines between 1981 and 2001 has been analysed in the literature (Neij *et al.*, 2003). The price umbrella identified above is evident in the Danish onshore wind energy sector (see Figure 5.3), where shakeout and sustained cost reduction did not occur until approximately 100MW of deployment had taken place. It should be noted that, upon comparison with unit deployments in the Danish Wind Turbine Master Register database (Energi Styrelsen, 2014), this corresponds to almost 1,400 wind turbine unit deployments.

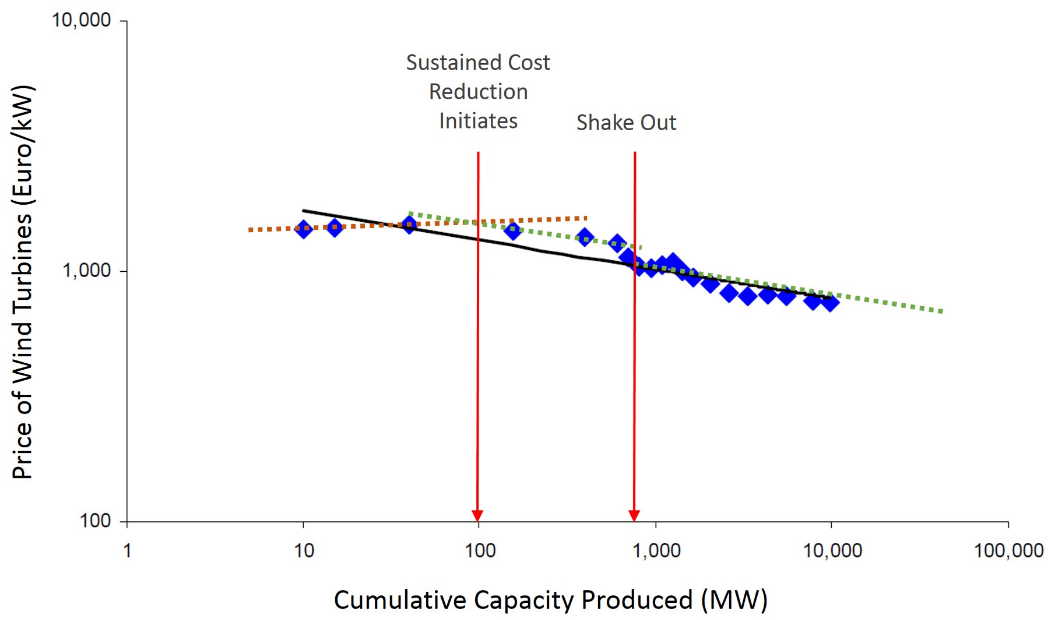

Figure 5.3: Capacity at which sustained cost reduction occurred in onshore wind turbines. Modified from Neij (2008)

5.4 Offshore Wind: Defining A Benchmark

This fluctuation in offshore wind costs is demonstrated in Figure 5.4, which considers offshore wind CAPEX costs (the whole system, including turbine components, installation, infrastructure and grid connection) over time.

By plotting offshore wind farm deployment with respect to the number of individual turbine units deployed, it was seen that, after a period of initial cost reduction, significant cost *increase* ensued, due to the more difficult project locations further from shore and in deeper waters, and the use of larger units that were still in development. The early cost reduction is perhaps linked to the nature of the turbines used. Early offshore wind turbine deployments utilitsed onshore wind turbine technology on offshore foundation structures, close to shore. Subsequent iteration led to offshore-specific turbine designs emerging. If the industry averaged cost per MW is used as the parameter of interest, it can be seen that sustained cost reduction was not achieved until over 2,500 unit deployments had taken place.

By using existing offshore wind deployment costs from industry (4C Offshore, 2012), adjusted in terms of industry averaged cost per MW and aligned with increasing levels of unit deployment, it was demonstrated that the cost of offshore wind at a European level appears to have plateaued at approximately 2,800 £/kW, as is shown in Figure 5.5.

In terms of future costs, a learning model for offshore wind was then generated as part of this research using the existing CAPEX costs presented as a function of unit deployment. Data on wind farm unit numbers and installation dates allowed a chronological catalogue of offshore wind deployment to be created (based on data available from online sources (4C Offshore, 2012)), this data is shown graphically in Figure 5.5. By considering only the cost of deployment for wind turbine numbers from unit 1,500 onwards (therefore ignoring the early increase in wind turbine cost/kW that was seen within the initial offshore wind deployments shown in Figure 5.5), which includes offshore wind farms installed between 2012 and 2015, and plotting the number of turbines deployed versus CAPEX cost per MW on a log-log scale (see Figure 5.6), a cost reduction trend was observed. A line of best fit was then applied to the data, where the equation of the line of best fit is of the form of Equation 3.3 (Chapter 3). The value of $-b$ was identified as -0.168. Calculation of the LR was then possible using Equation 3.4 from (3). This yields a representative averaged LR of approximately 11% for European offshore wind farm deployments since 2012. This learning rate, if assumed to apply to future offshore wind

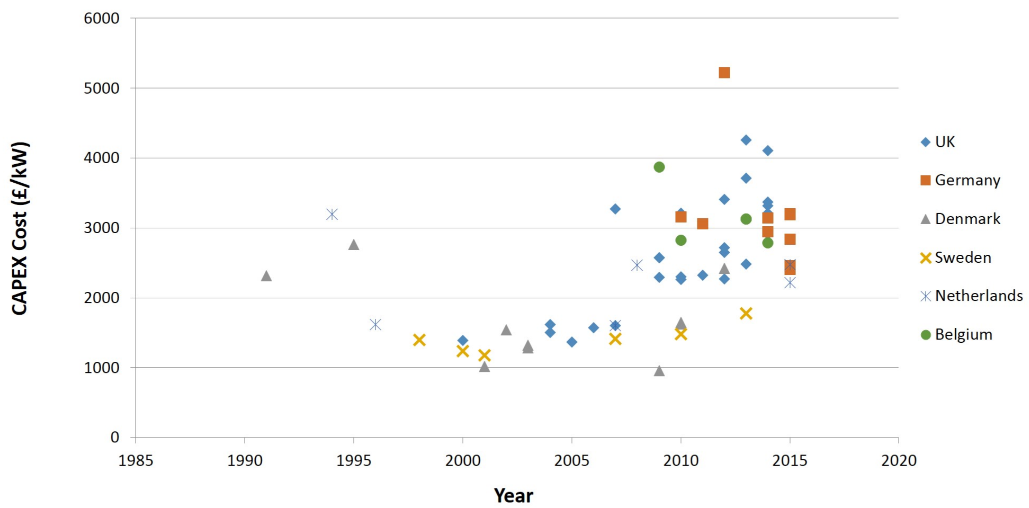

Figure 5.4: Offshore Wind Costs By Country. Source Data (4C Offshore, 2012)

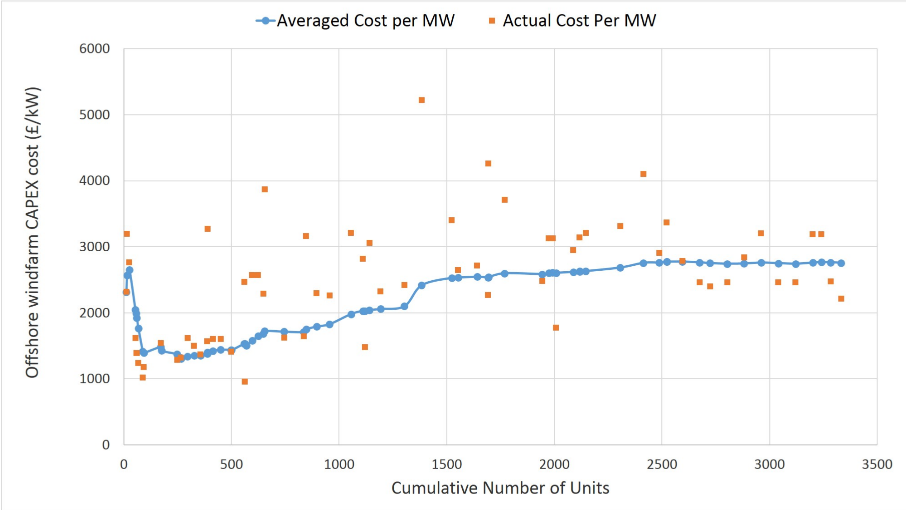

Figure 5.5: Offshore Wind Costs with Industry Progression (Actual cost and Industry Averaged cost (GBP)). Source Data (4C Offshore, 2012)

deployment, was then utilised for a representative cost reduction model for offshore wind. This is depicted in Figure 5.7. Assumed uncertainty bounds of $\pm 20\%$ were applied to the representative cost reduction model, as this then encapsulated the maximum and minimum cost variations within the time-frame from 2012 to the present day, and has been extended into future deployments as a plausible uncertainty range.

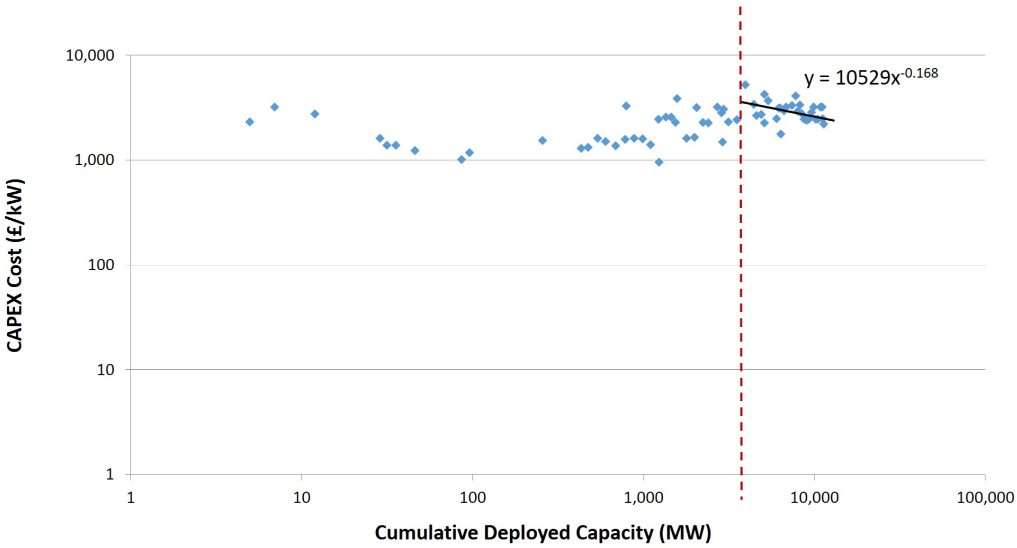

Figure 5.6: Offshore Wind Costs with line of best fit (power law).

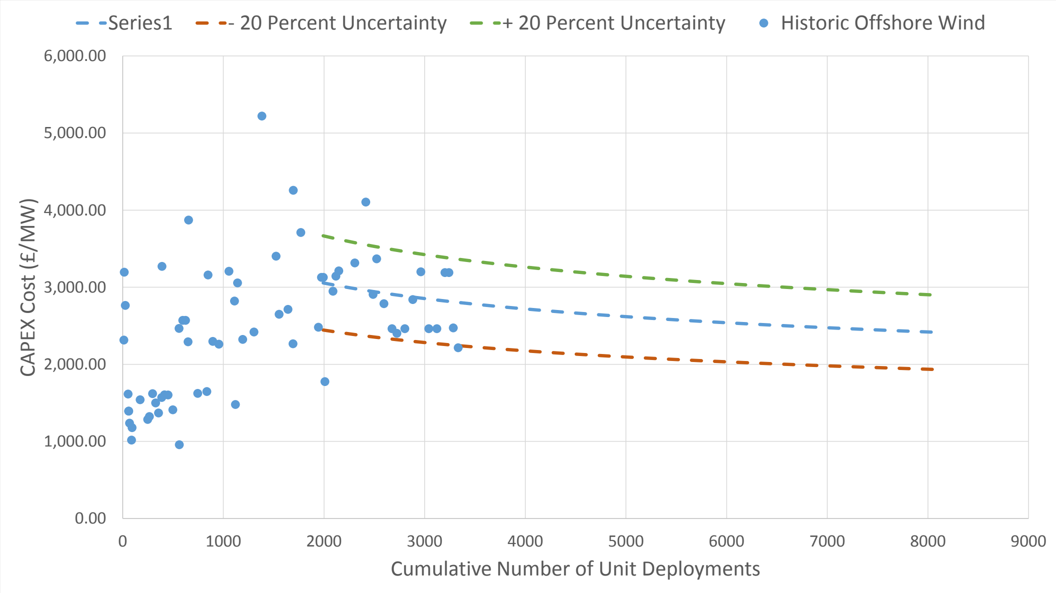

Figure 5.7: Offshore Wind Costs with future cost reduction trajectory estimate.

Rather than offering a fixed benchmark technology cost, the cost per kW of offshore wind is anticipated to fall as the technology matures – a moving baseline against which emerging marine renewable energy technologies may have to compete. It must be recognised that offshore wind energy deployment is taking place more rapidly that wave and tidal energy at the present time, and therefore the target for wave and tidal stream energy is likely to become progressively more difficult as offshore wind energy technology matures. However, for the purposes of this section, we assume a learning investment based on wave and tidal energy technologies reaching a target competitiveness with current offshore wind costs – a challenging task in and of itself, without considering any further cost reduction challenges. Taking current costs of offshore wind as a 'benchmark', the economic challenge of commercialising ocean energy – specifically in terms of the 'learning investment' – requires explicit treatment to enhance understanding, particularly with regard the major uncertainties and sensitivities involved.

5.5 Construction of a Cost Reduction Model

It should be noted that the sensitivity analysis presented within this research implicitly considers multiple generations of devices within the wave or tidal renewable energy sector as a whole, and so is not attempting to be technology or device specific. In order to facilitate a rapid calculation of several input parameter variations concurrently, a cost reduction model was developed within MATLAB to calculate a number of ocean energy learning curves (based upon input parameter ranges) simultaneously. A database of plausible learning curves would allow for effective calculation of the learning investment associated with each individual curve.

The basis of the model code was to allow calculation of all permutations of SC and CSCR for a given LR, then to identify the learning investment for each individual scenario. The individual learning curve for each viable permutation of the learning investment variables was calculated using Equations 3.3 and 3.4, as defined in Chapter 3, to define the CAPEX cost reduction with each device deployment. The model creates a database of CAPEX costs for each given device deployment, with each column in the database representing a specific LR, SC and CSCR permutation. The total number of scenario possibilities, based upon the product of number of SC, CSCR, and LR permutations, was 14,200 (71 SC permutations multiplied by 50 CSCR permutations multiplied by 4 LR permutations).

An assumed maximum deployment trajectory of 10,000 devices was used in order to curtail the computational intensity, and reflect a deployed capacity of 10GW using a large scale (1MW) device. It is also recognised that under certain conditions, cost reduction would not reach cost competitiveness with offshore wind within a plausible deployment trajectory.

A cost-reduction cut-off point was introduced at the point cost competitiveness was achieved, so that cost reduction did not continue once cost competitiveness with the offshore wind target cost was reached. The number of deployments required to achieve cost competitiveness within each scenario was readily available from the data generated by the code. Additionally, where cost competitiveness was not achieved within 10,000 unit deployments, this could also be clearly identified.

5.5.1 The Reference Case

As is acknowledged in previous work, marine energy commercialisation and large scale deployment is reliant on aggressive cost reduction from an early stage. Reference case assumptions for this chapter are based upon those used within existing literature on wave and tidal energy cost reduction (MacGillivray *et al.*, 2013a), as discussed within Section 5.2, where it was also outlined that the reference case does not represent a mid-range point of the uncertainty ranges. It represents an optimistic view on the future development of the wave and tidal energy sector – something which technology developers within the sector have largely presented as factually correct, despite the lack of empirical data to validate the assumptions made. This reference case uses an assumed learning rate of 12%, sustained cost reduction after the deployment of 20 devices, and a starting cost of 6,000 £/kW.

5.5.2 Outputs of the Code

In running the learning investment analysis, the output of the code was a database detailing CAPEX cost values for each unit deployed for each and every scenario (this allows cost reduction and learning cures to be plotted), stored within MATLAB under the variable name "Learning_Investment". In addition, the output included two 2-D plots: The first plot (for example, the plot displayed on the left of Figure 5.9) identified the overall learning investment for deployment of up to 10,000 devices under any given scenario (the model being capped at 10,000 units if cost competitiveness with offshore wind is not reached); the second plot (for example, the plot displayed on the right of Figure 5.9) identifies the CAPEX cost of the final device deployment within the model run (the 10,000$^{\text{th}}$ device) under any given scenario, to identify whether a particular scenario resulted in cost competitiveness with current offshore wind costs.

The learning investment output charts (introduced and explained in Figures 5.9 and 5.10) can be considered according to Figure 5.8, which depicts three zones, or areas, within the 2-D learning investment plot that can, at a high level, provide an initial overview of the learning investment characteristics for given input parameters. Area A represents the most attractive learning investment scenarios, scenarios in which relatively low learning investments can be achieved through rapid realisation of sustained cost reduction, or through low starting CAPEX costs for ocean energy technologies (or indeed a combination of both) – coloured dark blue in the learning investment charts that form the output of the model.

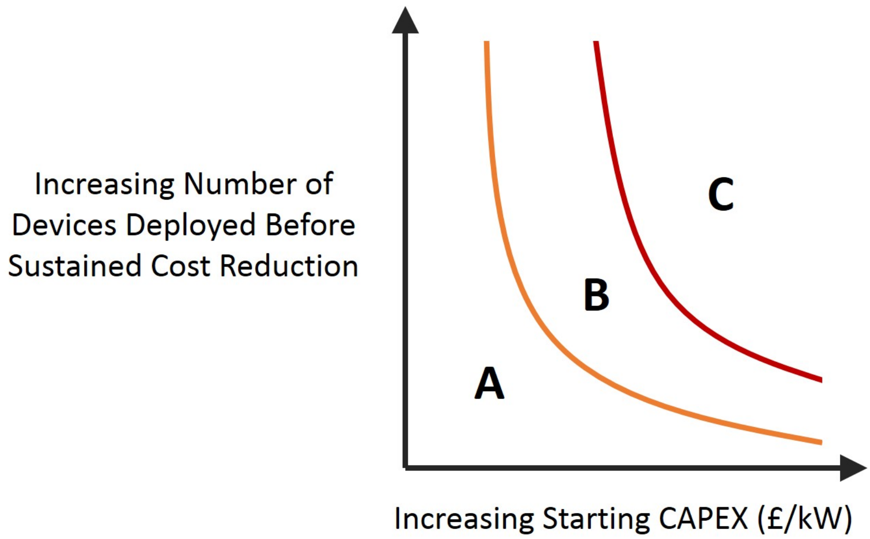

Figure 5.8: High Level Zones of Attractiveness.

Increasing starting CAPEX or increasing number of devices prior to sustained cost reduction (or a combination of both parameters simultaneously) will result in less attractive and significantly more costly learning investment scenarios, identified in area B, and are coloured light blue through to yellow in the learning investment charts that form the output of the model.

Area C represents the most costly learning investment scenarios, which occur either through high initial technology expense or in an inability of the technology to achieve early and sustained cost reduction, or an unfavourable combination of both parameters. Within the leaning investment charts that form the output of the model, Area C can be considered as the orange to red coloured areas within the chart. If the wave and tidal energy sectors are to achieve successful commercialisation, this area must be avoided.

Interpreting the Charts

The two side-by-side MATLAB output charts (as shown in Figure 5.9 and 5.10) can be interpreted as follows:

- First, a vertical line is drawn at the technology SC, the CAPEX cost of the device at the first deployment;
- Secondly, a horizontal line is drawn at the assumed CSCR;
- By identifying the point of intersection, and observing the appropriate learning investment value (left hand plot) or final device CAPEX (right hand plot), pertinent conclu-

sions can be drawn on specific scenarios;

- For the learning investment, the colour bar at the right hand side of the chart can be used to identify the learning investment cost under a given scenario;
- For the final device CAPEX, the interest is in whether or not cost competitiveness has been achieved. Where cost competitiveness within 10,000 unit deployments is achieved, this is indicated by the white coloured area within the chart.

Reference Scenario

For the reference scenario considered within this research, the lines are drawn at a SC of 6,000 £/kW (vertical) and a CSCR of 20 devices (horizontal). This is demonstrated in Figure 5.9. In this reference case, a total of 1,246 unit deployments are required in order to reach cost competitiveness with current offshore wind costs.

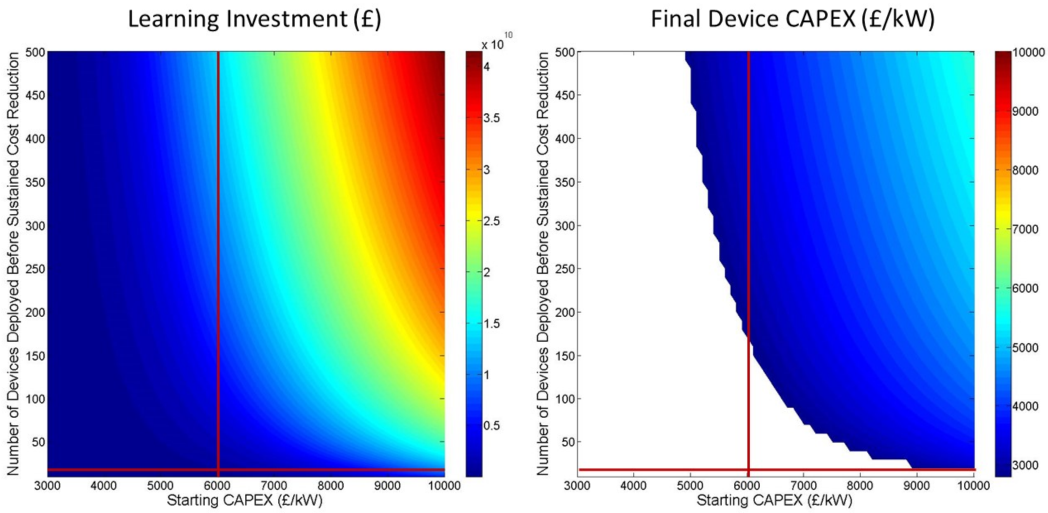

Figure 5.9: How to Interpret the Charts (Example One).

Taking the learning investment graph (left), it can be seen that the point of intersection corresponds approximately to a learning investment of between £500 million and £1 billion. Due to the scale on the right of the chart, this learning investment is very low in comparison to other scenarios. By interrogating the output database generated by the model, the learning investment for marine energy commercialisation under this scenario can be seen to be £760 million.

To investigate whether cost competitiveness with offshore wind was achieved, the final CAPEX graph (right) is used. We can confirm that cost competitiveness with offshore wind was reached in the reference scenario through investigation of the final CAPEX cost after 10,000 device deployments. Any ocean energy technology with a final installed CAPEX cost of 2,800 £/kW has reached cost competitiveness. In the case of our reference scenario, the point of intersection does indeed lie in the white coloured area corresponding to cost competitiveness with offshore wind.

It should be noted that, although the graphs provide an approximate visual indicator of the learning investment, quantitative values for each scenario are stored within the MATLAB data, and can be extracted from the relevant MATLAB variable "Learning_Investment".

Applying Perturbations

To investigate the effects of minor perturbations, a second example is examined. In this example, the SC is increased to 7,000 £/kW, and the CSCR is increased to 100 devices (it must be remembered that offshore wind reached over 2,000 unit deployments before sustained cost reduction was achieved, as shown in Figure 5.7). By finding the new point of intersection using the process described above, Figure 5.10 is produced.

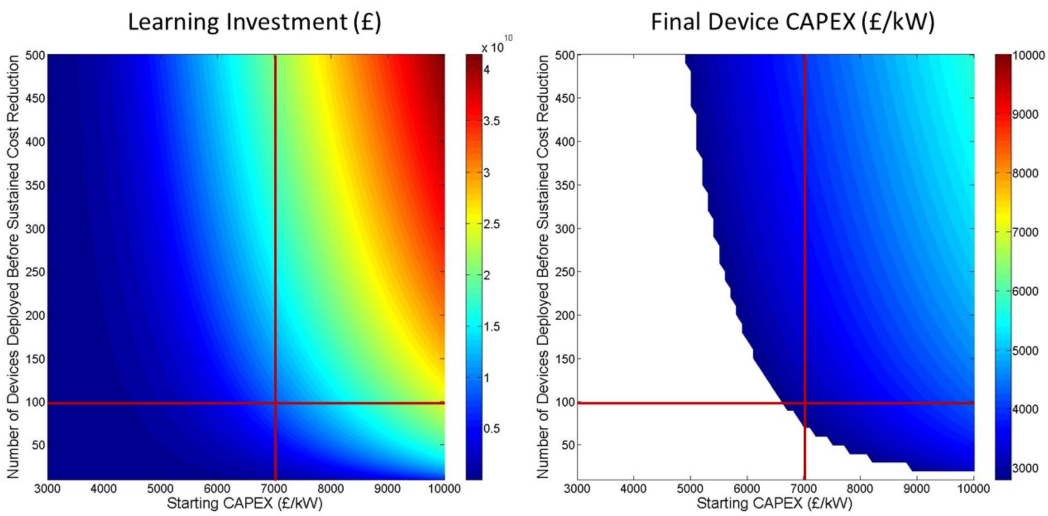

Figure 5.10: How to Interpret the Charts (Example Two).

Taking the learning investment graph (left), we can see that the point of intersection corresponds to a learning investment in the region of approximately £10 billion (cross-checking this with the MATLAB data provides the numerical value of this learning investment as £8.55

billion). In the case of the second example scenario, the final CAPEX graph (right) shows that the point of intersection lies at a value corresponding to 2,900-3,000 £/kW, and so cost competitiveness with 2015 offshore wind costs was not reached within 10,000 device deployments under this scenario.

We can therefore see that a relatively minor change to the input parameters has had a significant effect on the overall learning investment – the overall learning investment has increased by an order of magnitude in comparison to the reference case. This immediately provides warning on the risk and uncertainty within the ocean energy sector – the financial consequences of failing to meet optimistic deployment and cost reduction trajectories are severe.

5.6 Learning Investment Sensitivity Analysis

A sensitivity analysis was carried out to investigate the impact of perturbations in input parameters on the overall learning investment, and a number of individual scenarios were chosen as a basis of analysis. The analysis below explores the implication of divergence away from an early and sustained cost-reduction path. While it is not practical to discuss each of the 14,200 scenarios that have been modelled in detail, 23 scenarios have been selected for further analysis and discussion. These scenarios are presented in Table 5.1. A brief summary description of the scenarios, and an overview of why these scenarios were chosen is provided below:

- Scenarios 1 to 8 reflect a change in the SC of ocean energy technology, whilst maintaining all other variables (LR, CSCR) as per the Reference Scenario (Note: Scenario 4 represents the Reference Scenario);
- Scenarios 9 to 18 reflect changes in the CSCR, whilst maintaining all other variables (LR, SC) as per the Reference Scenario. The worst-case for CSCR within the context of this sensitivity analysis is set as 500 units – significantly lower than the 2,500 units experienced within the offshore wind sector;
- Scenarios 19 to 21 reflect changes in the assumed LR, whilst maintaining all other variables (SC, CSCR) as per the Reference Scenario;
- Scenario 22 reflects the absolute best case scenario as a result of optimistic combinations of different SC, LR and CSCR assumptions;

- Scenario 23 reflects the absolute worst case scenario as a result of pessimistic combinations of different SC, LR and CSCR assumptions;

Scenario	SC (£/kW)	CSCR (units)	LR (%)
1	3000	20	12
2	4000	20	12
3	5000	20	12
4	6000	20	12
5	7000	20	12
6	8000	20	12
7	9000	20	12
8	10000	20	12
9	6000	50	12
10	6000	100	12
11	6000	150	12
12	6000	200	12
13	6000	250	12
14	6000	300	12
15	6000	350	12
16	6000	400	12
17	6000	450	12
18	6000	500	12
19	6000	20	9
20	6000	20	15
21	6000	20	18
22	3000	10	18
23	10000	500	9

Table 5.1: Plausible Learning Investment Scenarios for Large Scale (1MW) Technology.

5.6.1 Variation of the Starting Cost

Early studies estimated the starting cost of marine energy at between £3,000 and £6,000 per installed kW (Callaghan and Boud, 2006). More recently, that estimated figure has risen – £6,000 to £10,000 per installed kW (Carbon Trust, 2011). Early predictions, which underestimated the challenges associated with deploying technology in the marine environment, were proven to have been over optimistic in terms of time-scale and cost (Kirk, 2009). However, most recent industry engagement has identified technologies with a claimed starting cost that is already almost competitive with offshore wind (SI Ocean, 2013; MacGillivray *et al.*, 2013a; Scotrenewables, 2014). For this marine energy learning investment investigation into the effect of a variation in SC, a sensitivity analysis was performed using SC at £1,000 increments from £3,000 to £10,000 per installed kW, reflecting uncertainty ranges within the research literature and industry consultation (Carbon Trust, 2011; SI Ocean, 2013). These were used in combination with a fixed 12% LR and an assumed CSCR of 20 device deployments, based on leading industry reports (Carbon Trust, 2011).

Figure 5.11 shows the changing learning curve profiles for the different SC assumptions. These curves were plotted using the outputs of the MATLAB model produced for this work. The reference scenario (SC_6000) results in a learning investment of £761 million, reaching cost competitiveness with current offshore wind costs after the deployment of 1,246 devices. The learning investment is highly sensitive to initial capital cost, varying from just under £4.74 million for a starting cost of £3,000/kW (with 29 devices deployed before cost competitiveness with offshore wind is reached) up to just over £10.9 billion for a starting cost £10,000/kW (10,000 devices deployed, but without reaching a level of cost-competitiveness with offshore wind). In other words, a 50% decrease in SC leads to an 99.4% decrease in learning investment. Conversely, a 66.7% increase in SC leads to a 1332% increase in learning investment requirements, without even achieving cost competitiveness within 10,000 unit deployments. The variations in SC are summarised in Table 5.2 and Figure 5.12.

It may reasonably be assumed that investors, whether public funding bodies or private sector institutions, may have a view of an acceptable investment in order to secure the benefits that marine energy could bring to the energy mix; however, an investment of over £10 billion is perhaps not an attractive option. To put the learning investments depicted in Table 5.2 into perspective, they are equivalent to a range of between approximately 0.016% and 36% of the 2014 UK expenditure on Research and Development, based on UK Gross Domestic

Figure 5.11: Learning Curves for Variation in Starting Cost.

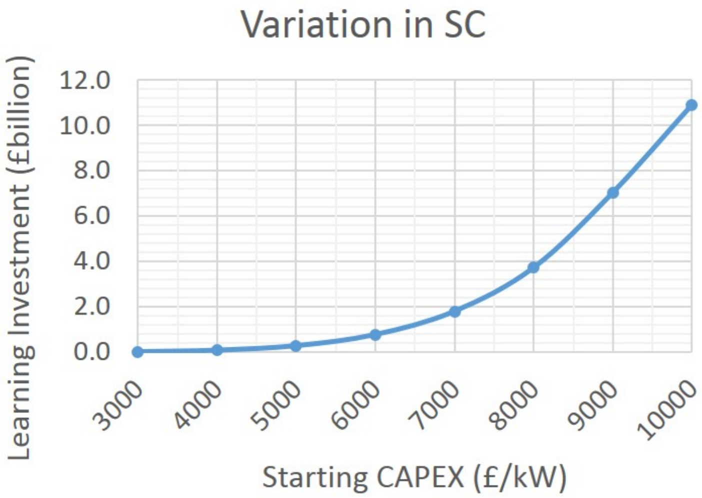

Figure 5.12: Learning Investment versus change in Starting Cost.

Expenditure on R&D (GERD) of £30 billion (Gruebler and Studt, 2014). This is a significant learning investment variation under what is a relatively small variation in input assumptions. The implication here is that upscaling in manufacture of a new product without revenue from sales and learning from past deployment does not necessarily lead directly on to reduced costs. A failure to develop low cost technologies will mean that the market and a single government alone will not be able to afford the costs associated with the learning investment.

Scenario	SC (£/kW)	# of deployments to reach cost-competitiveness	Learning Investment (£million)	Deviation from Reference Case (%)
1	3000	29	4.74	-99
2	4000	138	68.9	-91
3	5000	463	270	-65
4	6000	1246	761	0
5	7000	2875	1790	+135
6	8000	5932	3720	+389
7	9000	>10000	7030*	+825
8	10000	>10000	10900*	+1336

Table 5.2: Variation in Starting Cost. The * denotes that cost competitiveness with current offshore wind costs was not achieved within 10,000 device deployments.

5.6.2 Variation of the Capacity at which Sustained Cost Reduction occurs

It is naïve and potentially misleading to suggest that sustained cost reduction will occur from the moment the first prototype of a novel technology is installed. It is more realistic to anticipate costs may rise during early deployment as part of the necessary experience required to facilitate later cost reductions, as has been discussed earlier within this section and was experienced within the offshore wind energy sector (Kirk, 2009). The phenomenon of early cost increases are not uncommon during early stage deployment (Watson *et al.*, 2012), and indeed, should perhaps be anticipated within an emerging industry such as marine renewables.

To further explore marine energy learning investment, a sensitivity analysis was performed on the CSCR at 50 device increments from 50 devices to 500 devices. Many wave and tidal energy technology developers are anticipating rapid transition to sustained cost reduction from as low as 10 devices. However, given that offshore wind deployed over 2,500 units before sustained cost reduction was became evident, our analysis reflects a plausible range given the uncertainty at this stage in development. A fixed LR of 12% and a SC of £6,000 per installed kW were assumed.

Figure 5.13 shows the changing learning curve profiles for the different assumptions of unit deployment levels before sustained cost reduction occurs. The learning investment varies from £761 million for a CSCR of 20 units up to £13.7 billion for a CSCR of 500 units (10,000 devices deployed, but without reaching a level of cost-competitiveness with offshore wind). The worst case scenario (CSCR of 500 units) results in a 1,700% increase in learning investment requirements compared to the reference scenario. The variations in CSCR are summarised in

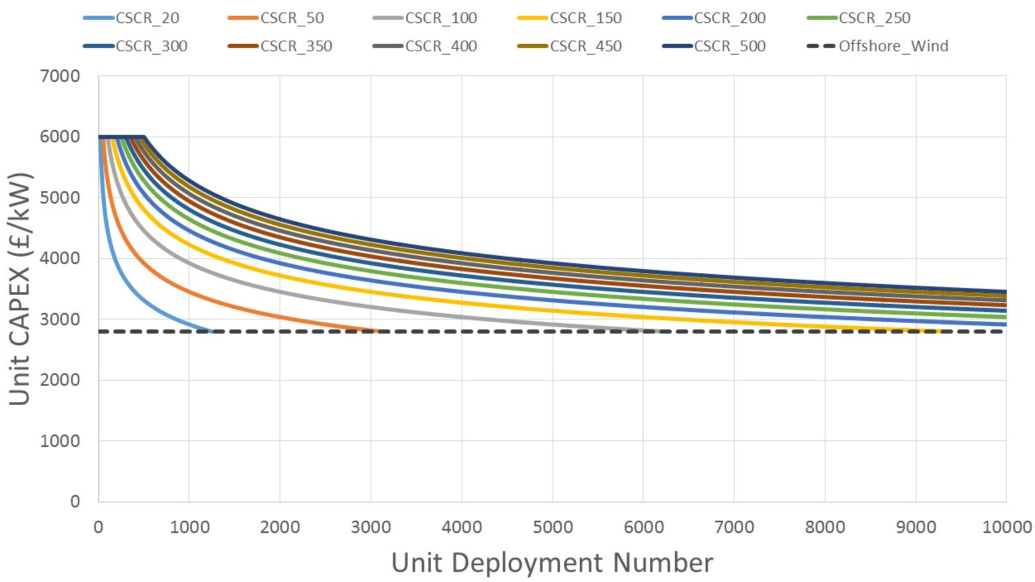

Figure 5.13: Learning Curves for Variation in units deployed before sustained cost reduction occurs.

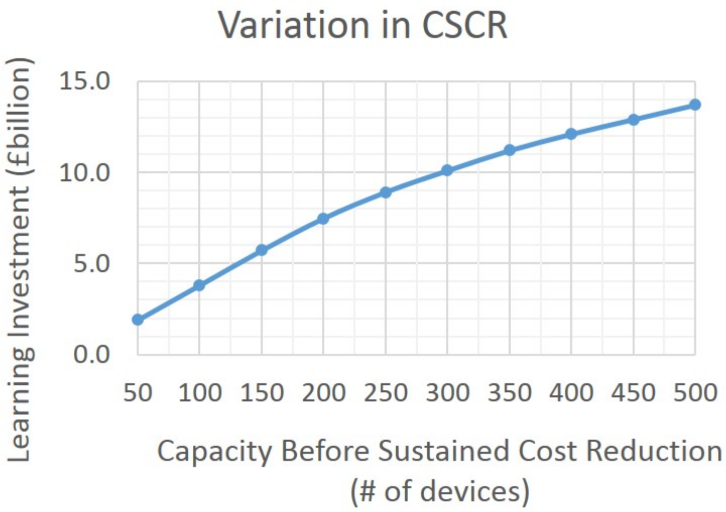

Figure 5.14: Learning Investment versus change in CSCR.

Table 5.3 and Figure 5.14.

In the scenarios above, if marine renewable energy proves unable to achieve sustained cost reductions until after 200 units are deployed, then cost competitiveness with offshore wind will not be reached within a 10,000 device deployment scenario. The implication here is that the marine energy sector must minimise the required CSCR if cost competitiveness with offshore

Scenario	CSCR (Devices)	# of deployments to reach cost-competitiveness	Learning Investment (£million)	Deviation from Reference Case (%)
4	20	1246	761	0
9	50	3116	1900	+150
10	100	6233	3810	+401
11	150	9350	5720	+651
12	200	>10000	7480*	+884
13	250	>10000	8920*	+1072
14	300	>10000	10100*	+1231
15	350	>10000	11200*	+1368
16	400	>10000	12100*	+1489
17	450	>10000	12900*	+1598
18	500	>10000	13700*	+1696

Table 5.3: Variation in unit deployment before sustained cost reduction. The * denotes that cost competitiveness with current offshore wind costs was not achieved within 10,000 device deployments.

wind is to be achieved within a 10GW deployed capacity. There is an impetus not to make the same mistakes that were made in offshore wind deployment, in which sustained cost reduction trends are only being established after deployment of over 2,500 units.

5.6.3 Variation of the Learning Rate

Multiple causal factors underpin an observed aggregate learning rate – learning by research, learning by experience, scale and volume effects, knowledge spillovers and transfer. These forces interact in different ways over the development history of technologies, generating changes in observed learning rates for retrospective studies, and uncertainty ranges for prospective studies. For example, learning rates of up to 19% have been observed in the wind energy industry over certain periods (Junginger *et al.*, 2010b). However, examples of where the wind industry achieved much lower learning rates have also been seen; for example, in Germany, between 1996 and 2001, a learning rate of -1% was estimated – a 5-year period of slight cost increases (Junginger *et al.*, 2010b).

For marine renewable energy, a learning investment sensitivity analysis was carried out using LR of 9%, 12%, 15% and 18%, while using a fixed CSCR of 20 devices and a SC of £6,000 per installed kW.

Figure 5.15 shows the changing learning curve profiles for the different LR assumptions. The learning investment is highly sensitive to LR, varying from £272 million for a LR of 18%

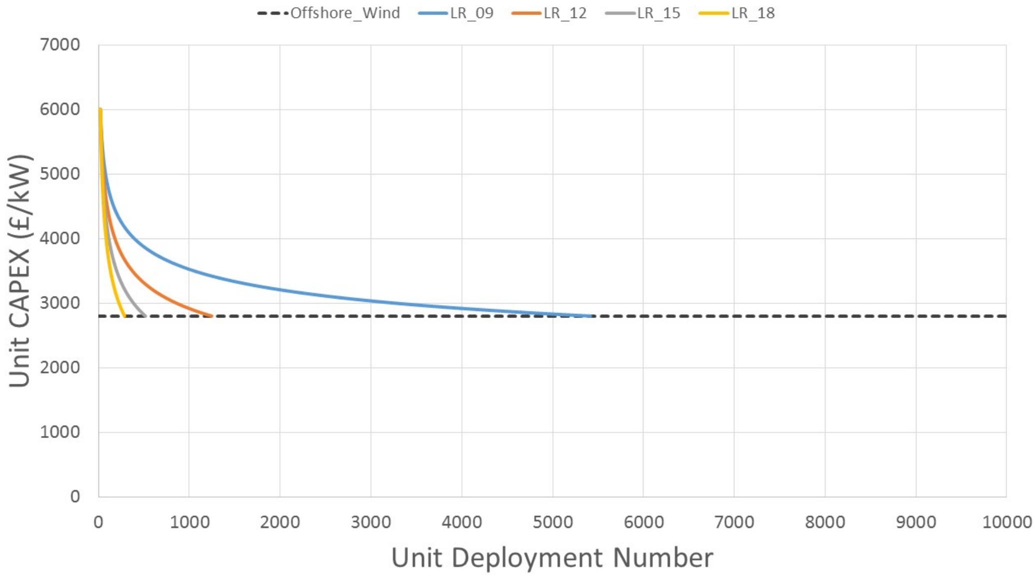

Figure 5.15: Learning Curves for Variation in Learning Rate.

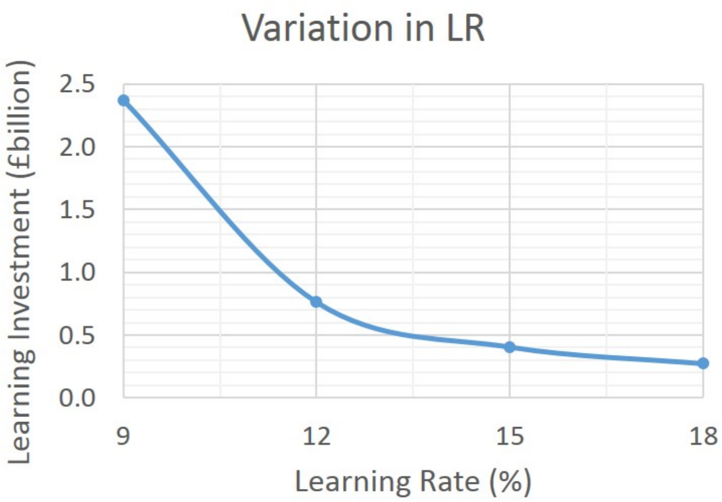

Figure 5.16: Learning Investment versus change in Learning Rate.

up to £2.37 billion for a LR of 9%. The latter figure represents the learning investment after 10,000 unit deployments, as in this scenario, marine energy technologies do not achieve cost competitiveness with offshore wind. In other words, increasing the LR by 6 percentage points (so that LR = 18%) leads to a 64% decrease in learning investment. In the worst case scenario considered, decreasing the LR by 3 percentage points (so that LR = 9%) leads to a 211% increase in learning investment requirements. The variations in LR are summarised in Table

5.4 and Figure 5.16.

Scenario	Learning Rate (%)	# of deployments to reach cost-competitiveness	Learning Investment (£million)	Deviation from Reference Case (%)
4	12	1246	761	0
19	9	5416	2370	+211
20	15	516	404	-47
21	18	286	272	-64

Table 5.4: Variation in Learning Rate.

In the scenarios above, favourable SC and CSCR parameters are used, therefore scenarios 4, 19, 20 and 21 all result in cost competitiveness with offshore wind being achieved. The learning rate can be seen to significantly alter the level of deployment at which this occurs. At the present time, it is impossible to state with any degree of certainty what the learning rate for ocean energy technologies will be, which presents a large risk for the long term commercialisation costs. Any failure to achieve a rapid and consistent level of cost reduction will reduce the attractiveness of continued deployment considerably.

Finally, considering the best case and worst case scenarios under the given input parameter ranges allows the full uncertainty of the economic requirement to be made clear, shown in Table 5.5. The plausible range of learning investments spans five order of magnitude – from millions to tens of billions. It can be clearly seen that small perturbations to the input parameters cause significant implications for the overall learning investment requirements.

Scenario	Starting Cost (£/kW)	CSCR (Devices) CSCR	Learning Rate (%)	# of deploy. to cost-comp.	Learning Investment (£m)	Deviation from Ref. Case (%)
22	3000	10	18	12	2.17	-99.7
23	10000	500	9	>10000	48200*	+6238

Table 5.5: Variation in all parameters.

5.7 Learning Investment Sensitivity Analysis Results

Analysis yielded output graphs for each learning rate considered within the study (9%, 12%, 15% and 18%), which can be found in Appendix F. The analytical solutions are stored within a variable called “Learning_Investment”, saved in the MATLAB code. The relevant file can be queried in order to find the specific learning investment values for given input parameters, but the charts provide a convenient reference from which to view results graphically. The overarching theme of the output charts is that there is a significant impact on learning investment arising from relatively modest changes to the input parameters. This is highlighted in Figure 5.17, which illustrates that an increase in SC from £7,000/kW to £9,000/kW and an increase in CSCR from 50 units to 100 units (whilst maintaining a consistent 12% LR) results in a threefold increase in learning investment – increasing from £5 billion to £15 billion. Furthermore, this change in input parameters also results in a failure to achieve cost competitiveness with offshore wind within a 10,000 unit deployment scenario.

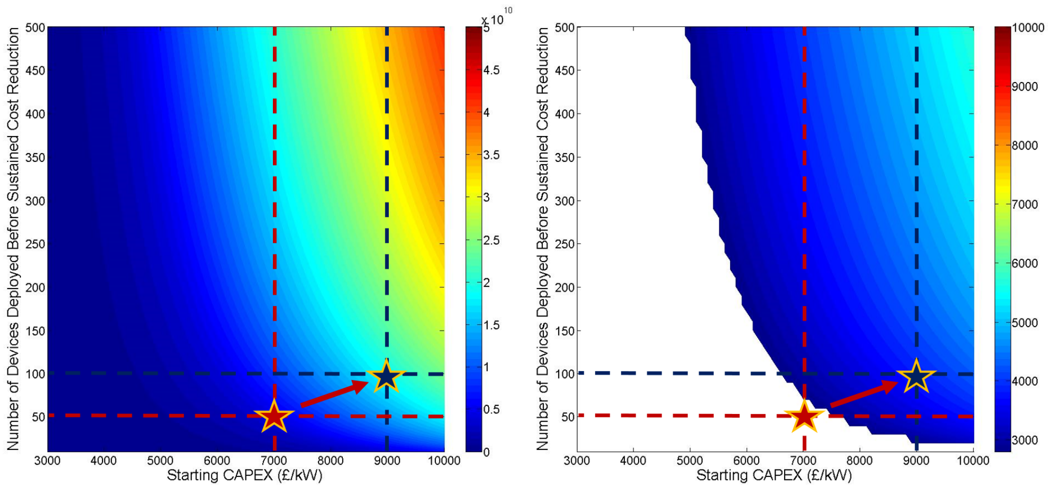

Figure 5.17: Example of Small Perturbation to Inputs on Learning Investment Outcome.

5.8 Effects of Scale on Learning Investment

MW-scale technology development is not the only environment in which technology research, development, innovation, demonstration and deployment is taking place. Tocardo International BV, a Dutch company producing run of river and tidal current turbines, has successfully sold devices to customers for use in river applications across the world. Three 100kW T1 device have also been installed within the Afsluitdijk storm barrier in the Netherlands, and a five turbine array (of 200kW T2 devices) has been installed within the Oosterschelde storm barrier. A T1 device can be procured from Tocardo for a cost of £242k, a cost that included the turbine and power conditioning equipment up to the point of connection with the export cable (Personal Communication, 2014). The larger 200kW T2 device was estimated to cost approximately £400k based upon a discussion with the technology developer (Personal Communication, 2014).

Recent analysis carried out for Ocean Energy Systems (OES) suggested that the device could account for approximately 46% of the total project cost for early array projects (Ocean Energy Systems, 2015). Taking this into account, and using the CAPEX costs outlined above, approximate project costs using Tocardo T1 devices could be in the region of 5,300 £/kW. This is also consistent with projected costs for modular tidal energy projects aiming to offer an alternative to stand alone diesel generators (NIOZ Royal Netherlands Institute for Sea Research, 2015).

Albatern, a wave energy device developer based in Scotland, has been developing a wave energy converter that can be installed in arrays by coupling together modular, scaleable 'Squid' units. The design principles behind this technology have led to a 'starting-small' approach, with initial units capable of producing a peak output of 7.5kW. The second generation Squid unit is anticipated to produce an output of 75kW. Albatern were provisionally awarded £1.8 million funding through the WATERS III programme, towards a total project cost of £3.5 million. If this total project cost can be assumed to result in the development, fabrication and installation of three 75kW Squid devices, then a unit cost of approximately 16,000 £/kW is estimated.

Given that the assumptions made in the MW-scale learning investment analysis covered a range of scenario possibilities under a range of input parameters, it would be appropriate to apply the same LR and CSCR assumptions to an investigation surrounding the use of small-scale technology, which represents a sub-MW class device – hereafter taken to be a 100kW unit. The starting cost range used within this analysis will be 5,000 – 16,000 £/kW, to encapsulate a range of variations with a higher cost per kW than considered previously within the large scale technology learning investment analysis. The new parameter ranges are as follows:

1. The SC marine technology deployment and connection was varied at 250 £/kW increments, from a reference of 10,000 £/kW, between 5,000 £/kW and 16,000 £/kW;
2. The assumed LR was a reference of 12%, and high/low scenarios of 15% and 9% respectively, based on data within an industry leading report (Carbon Trust, 2011). An additional scenario of 18% was included as higher learning rates could be seen in early technology development of high cost equipment, reflecting what was achieved within the early solar PV sector;
3. The CSCR was varied at increments of 10 devices, from a reference of 20 devices,

between 10 and 500 devices.

A number of plausible learning investment scenarios were generated for the small scale technology innovation pathway, as depicted in Table 5.6.

Scenario	SC (£/kW)	CSCR (Devices)	LR (%)	Learning Investment (£m)
1	10000	20	12	1093*
2	5000	10	9	30.4
3	5000	10	12	13.4
4	5000	10	15	8.5
5	5000	100	9	305
6	5000	100	12	135
7	5000	100	15	86.3
8	5000	500	9	1011*
9	5000	500	12	672
10	5000	500	15	432
11	10000	10	9	1720*
12	10000	10	12	627
13	10000	10	15	192
14	10000	100	9	3370*
15	10000	100	12	2421*
16	10000	100	15	1606
17	10000	500	9	4821*
18	10000	500	12	4143*
19	10000	500	15	3518
20	16000	10	9	4432*
21	16000	10	12	2683*
22	16000	10	15	1332*
23	16000	100	9	7072*
24	16000	100	12	5554*
25	16000	100	15	4250*
26	16000	500	9	9394*
27	16000	500	12	8309*
28	16000	500	15	7309*
29	5000	10	18	6.4

Table 5.6: Plausible Learning Investment Scenarios for Small Scale (100kW) Technology. The * denotes that cost competitiveness with current offshore wind costs was not achieved within 10,000 device deployments.

As was the case with the learning investment sensitivity analysis using large scale technology, there is a large deviation in potential learning investments when small perturbations are made to input parameters. However, when considering similar input parameters to that of the large scale technology case study, the magnitude of the learning investment is significantly lower in the case of small scale technology for a given number of unit deployments.

However, as has been argued in the previous section of this chapter, wave and tidal energy technologies have been attempting to bypass a formative phase of technology development and proceed on to rapid unit and industry up-scaling. This approach is counter-intuitive to the way in which historic energy sector technologies have developed. If the focus is on the first 1,000 unit deployments, and these are considered to represent a formative phase of development whereby bankable technology may not yet exist, where a number of performance optimisations are yet to be made, and in which the stage of development may see early failures and unforeseen events, the total investment and learning investment for small scale technology is far more palatable than that of MW-scale technology.

It must be emphasised that the assumptions for large-scale and small-scale models result in very different values for final installed capacity. A deployment of 10,000 large-scale units would result in an installed capacity of 10GW, whereas 10,000 small-scale units would only result in an installed capacity of 1GW. For an identical number of unit deployments, the installed capacity using small-scale technology would only be one-tenth of that using large-scale technology. Considering the best-case scenarios, the point in which cost competitiveness is reached for both large and small-scale technologies results in a similar deployed capacity, however the small-scale technology will have a ten-fold increase in the number of units deployed. Best and worst case scenarios are summarised in Figure 5.18, however, it should be noted that the 'best case' for both large-scale and small-scale technologies represents very unrealistic scenarios.

Chapter 4 outlined the importance of iteration and deployment within a formative phase. Installed capacity will become important as a technology demonstrates maturity, but until such a time as this has been demonstrated, installed capacity should not be the primary metric of focus – rather iteration and optimisation through deployment, and the successful demonstration of kWh generated. For a given cost, a significantly larger number of unit iterations and deployments can take place using small scale technology. Until successful technology emerges from a formative phase of development, then the economic argument favours the deployment of small-scale technology, in which a larger number of unit iterations and deployments will

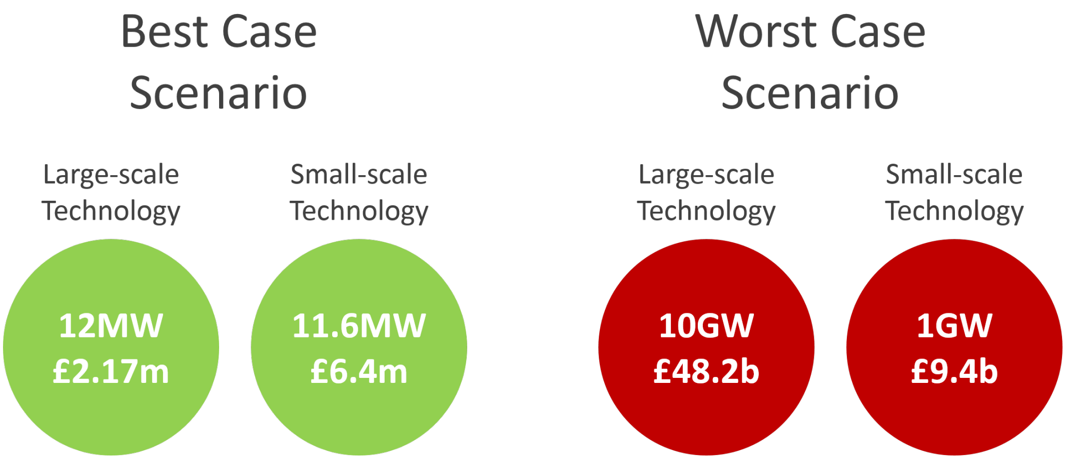

Figure 5.18: Summary of Best Case and Worst Case Scenarios for Large and Small-Scale Technology.

allow greater levels of learning by doing.

The ease of scalability of WECs and TECs differs significantly, and this point is again acknowledged (see Section 4.5). For wave energy, where the resource and methods of extraction are significantly more complex than for tidal (or wind), the ability to scale technology is a lot less straightforward.

5.9 Monte Carlo Simulations

The previous sections have discussed the implications of deviation from assumed parameters by providing the reported outputs from a selection of scenarios, and visual depiction of the full range of possible deterministic scenarios. This is a mechanism for identifying the learning investment outcome (and whether a technology has reached cost-competitiveness with offshore wind) for any eventuality, or any permutation of input parameters.

However, there are probabilities associated with each of the input parameters: some input parameters are more likely to occur than others, which in turn would result in certain learning investment scenarios becoming more likely to occur than others. Indeed, certain scenarios such as the worst case assumption should see a much lower probability of occurrence than the mean learning investment.

Monte Carlo analysis is a statistical analysis tool to investigate the probability-value relationship for a number of variable input parameters (Murtha, 1997). Monte Carlo simulations are widely used in scientific, engineering, financial and business applications where an estimate, forecast, or decision must be made under conditions of significant uncertainty. Given the discussion already presented within this chapter surrounding marine energy economic uncertainty, Monte Carlo simulations are deemed, for the purposes of this research, to be a good mechanism for estimating the more probable learning investment outcomes for ocean energy technologies given uncertainty in the input parameters SC, LI, and CSCR.

With Monte Carlo simulations, a number of random events can be simulated, providing a representative portion of all the plausible scenarios, analysis of which can provide an effective means of reaching an analytical solution where exhaustive numerical evaluation is too computationally expensive or time consuming. It allows the risk to be more explicitly analysed and offers an improvement over simple sensitivity analysis or best / worst or average case scenario analysis.

5.9.1 Building the Model

The Monte Carlo simulation model produced for this research is essentially and adaptation and evolution of the learning investment sensitivity cost model that was created for the work in Section 5.5.

The learning investment cost model contained all the necessary parameter variables for the Monte Carlo simulations, but the code was modified so that automated random scenario selection would occur, selecting a LR, SC and CSCR for each deployment within the analysis – based upon probability distributions for each input parameter, defined later. A Gaussian distribution was assumed in each case due to the statistical convenience of the ability to represent the distribution using two parameters – the mean, and the standard deviation. Given that the estimated SC for technology is dependent on unit scale, two models will be built – the first for large-scale units, and the second for small-scale units.

In this economic analysis, the concern is the most likely learning investment cost. As has already been discussed, small perturbations to the three input parameters of LR, SC, and CSCR can result in large changes to the overall learning investment requirements. For the Monte Carlo simulations, probability density functions (PDF) of each of the input variables are required. Normal distributions were chosen to represent the probability distribution for each of the input parameters, which were defined by a mean and standard deviation for each parameter. The distribution for SC was defined by the responses from stakeholder engagement, while for LR and CSCR, the distributions were subjectively chosen to reflect analysis carried out within the earlier studies of this chapter.

Starting Cost (SC) – Large Scale Technology

Public reports are available detailing the results of various cost of energy projects (SI Ocean, 2013; MacGillivray *et al.*, 2013a; Ocean Energy Systems, 2015), but the cost data which was gathered are sensitive information, and thus individual technology developers and individual unit costs cannot be disclosed. However, due to participation within these projects, access to the raw data has ascertained that the cost data can be represented within a normal distribution with mean of 7,100 £/kW and standard deviation of 1,300 £/kW. This encapsulates the full range of costs that were returned from the stakeholder engagement for MW-scale technology, assuming that maximum and minimum costs within the collected dataset represent three standard deviations from the mean value – ensuring that 99.7% of data points will fall within the parameter range identified. The PDF for the SC distribution for MW-scale technologies is shown in Figure 5.19. This is the only PDF that will be displayed graphically, and the mean and standard deviation for all remaining PDFs will be outlined in Section 5.9.1.

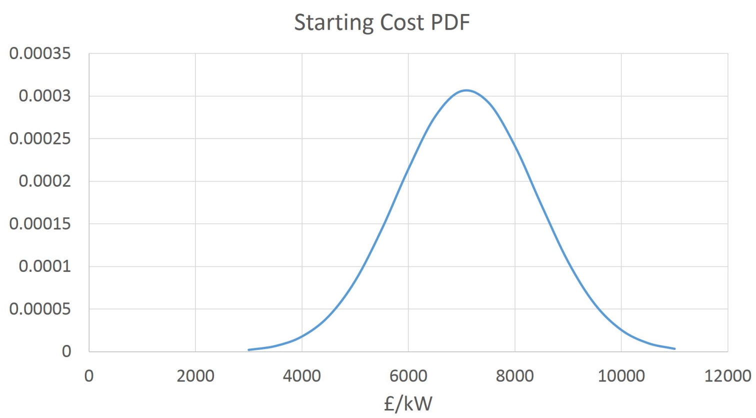

Figure 5.19: Probability Density Function for Large-Scale Technology Starting Cost

Starting Cost (SC) – Small Scale Technology

As with the large scale technology costs, stakeholder engagement provided a range of responses for capital costs for sub-MW-scale technologies in the region of 100kW in scale (Ocean Energy Systems, 2015). The cost data which was gathered are sensitive information, and thus individual technology developers unit costs cannot be disclosed.

However, a normal distribution with mean of 10,000 £/kW and standard deviation of 2,000 £/kW again encapsulates the full range of costs that were returned from the stakeholder engagement for kW-scale technology.

Capacity before Sustained Cost Reduction (CSCR)

Industry reports are, at present, utilising optimistic assumptions around the point at which sustained cost reduction will occur. Reports have generally used a 1MW device, with doubling capacities of 10MW or 20 MW (Carbon Trust, 2011; SI Ocean, 2013) in which to model sustained cost reduction. Analysis of cost reduction in the wind energy sector has shown that over 100MW was deployed prior to industry shakeout and sustained cost reduction being achieved (Neij *et al.*, 2003), as was demonstrated in Figure 5.3. This 100MW capacity constituted several hundred kW-scale wind turbines, and so the number of units deployed was far greater than the cumulative capacity would perhaps suggest. If the wind energy shakeout and CSCR is considered with respect to number of unit deployments, it would represent approximately 1,369 unit deployments (using the Danish Wind Turbine Master Register to cross reference unit deployments with 100MW total deployed capacity (Energi Styrelsen, 2014)).

In order to become cost competitive with incumbent technology, wave and tidal energy technologies cannot follow a cost reduction trajectory similar to that of wind – if the technology is to become commercially competitive, cost reduction must be achieved in an accelerated fashion. An assumed shakeout after 10 or 20 device deployments is an altogether unrealistic assumption for the industry as a whole. It is here proposed that the PDF for CSCR will utilise a mean value of 100 unit deployments, with a standard deviation of 20. This number has been selected generically to represent a value larger than existing ocean energy modelling, but below that experienced within the wind energy sector (recognising that accelerated cost reduction is essential in wave and tidal energy). It should be noted that the model itself is capable of being run with alternative PDF inputs, however, for the purpose of this research, multiple runs will not be considered.

This suggested range for CSCR may still be optimistic in comparison to wind energy, but represents perhaps a more realistic distribution of possibilities than the estimates made within industry reporting to date. In addition, if the wave and tidal energy sectors do not reach rapid consolidation on leading designs, then the ability of technology to achieve extensive cost reduction may be impaired. Over 13 large scale prototype devices have been installed in UK waters, four of which were 1MW in capacity, but there is little evidence to suggest that continued or sustained cost reduction is taking place – these prototype deployments are still too few to determine whether significant long-term cost reduction trends exist. It is recognised that this 100 unit deployment estimation is subjective, but it should be noted that historical evidence suggests that the wave and tidal energy sector's assumptions to date have been inherently optimistic, and this research aims to provide a tempered approach to cost reduction expectations and forecasts in marine energy. The CSCR PDF was kept consistent regardless of technology scale, thus was identical in both large-scale and small-scale models.

Learning Rate (LR)

The learning rates considered within the scope of this Monte Carlo model (6%, 9%, 12%, 15%, and 18%) have a mean of 12, and a standard deviation of 4.24. A number of learning rates have been experienced by individual technologies historically, with evidence in the literature providing the means of justification for our selection range of learning rates (Rubin *et al.*, 2015). We assume that these learning rate ranges are representative of the range of learning rates that could be achieved by a marine renewable energy technology. The LR PDF was kept consistent regardless of technology scale, thus was identical in both the large-scale and small-scale models.

PDF Mean and Standard Deviation Summary

The PDF for each parameter are summarised within Table 5.7.

Parameter	Mean	Standard Deviation
Large-scale SC (£)	7,100	1,300
Small-scale SC (£)	10,000	2,000
LR (%)	12	4.24
CSCR (units)	100	20

Table 5.7: Mean and Standard Deviations for each PDF.

5.9.2 Probability Density Functions for Learning Investment and Total Investment

To plot the resultant learning investment and total investment PDF, it first needs to be determined which type of distribution the output dataset best fits. Observation of the learning investment and total investment output statistics – the frequency of occurrence for learning investments, broken down into appropriate interval ranges – suggests that data are right-skewed (positively skewed), the mean value of the distribution is greater than the median and mode, and a long tail to the right of the chart can be seen (see Figures 5.20 and 5.21).

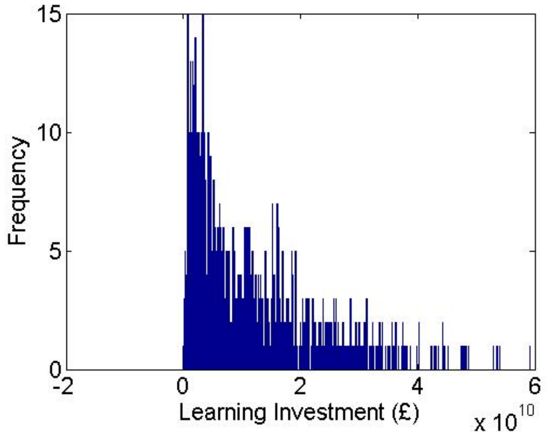

Figure 5.20: Right-Skewed Distribution: Monte Carlo Analysis Simulating 1,000 Scenario Possibilities, Given the Defined PDF of Input Variables for Large Scale Technology

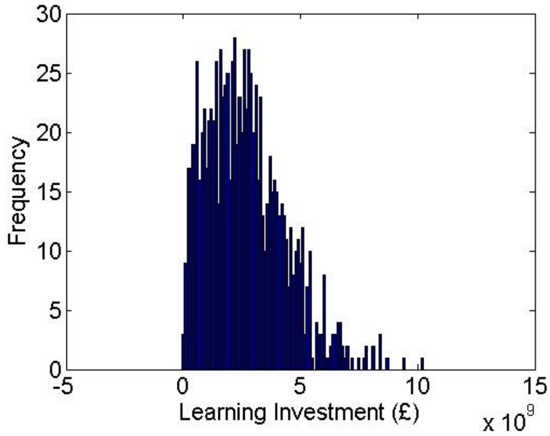

Figure 5.21: Right-Skewed Distribution: Monte Carlo Analysis Simulating 1,000 Scenario Possibilities, Given the Defined PDF of Input Variables for Small Scale Technology

For heavily skewed distributions, or distributions that contain outliers, a normal distribution is not considered appropriate (Navidi, 2011). Alternative distributions that could be considered in the case of right-skewed data include lognormal, Weibull, Gamma, or Chi-squared (NIST and Sematech, 2015). In order to select the most appropriate distribution for the data produced by the model, we must observe Quantile-Quantile (Q-Q) plots for each distribution type. A Q-Q plot is a graphical method of comparing the quantiles from a probability distribution from a known dataset against the quantiles from a theoretical distribution of a given type. Q-Q plots will identify whether the theoretical distribution type is suitable – if the reference distribution is appropriate for modelling the distribution of the known dataset, the Q-Q plot will fall approximately along a linear reference line.

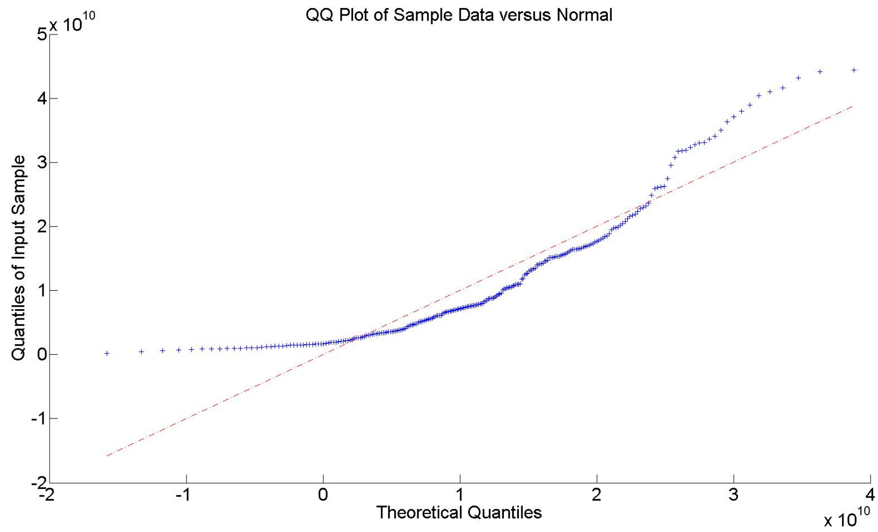

Figure 5.22: Normal Distribution Incompatibility with Large-scale Technology Data

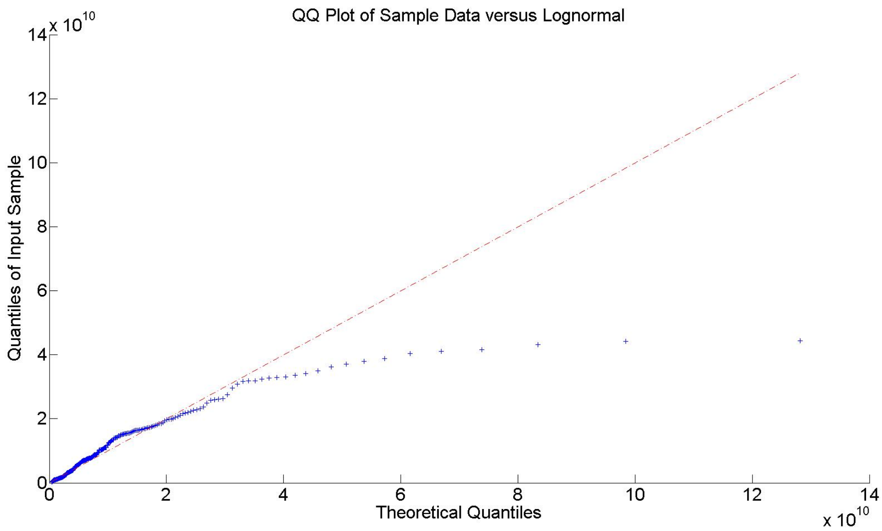

Figure 5.23: Lognormal Distribution Inompatibility with Large-scale Technology Data

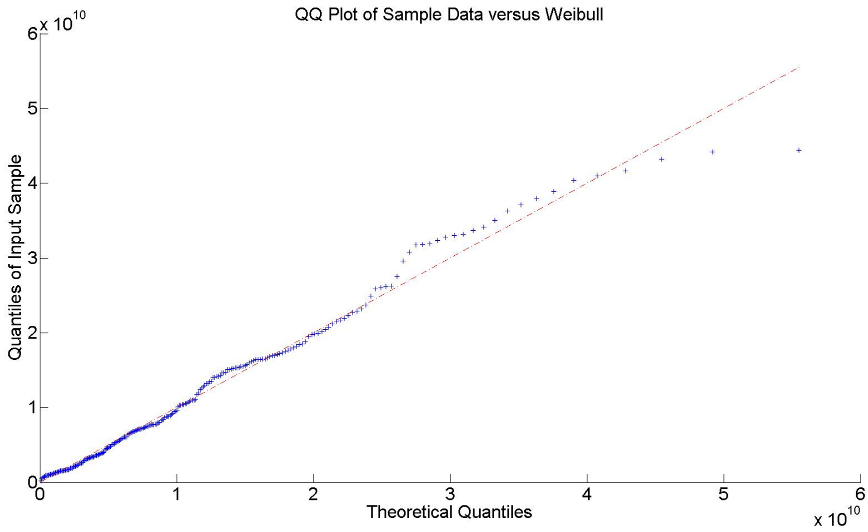

Figure 5.24: Weibull Distribution Compatibility with Large-scale Technology Data

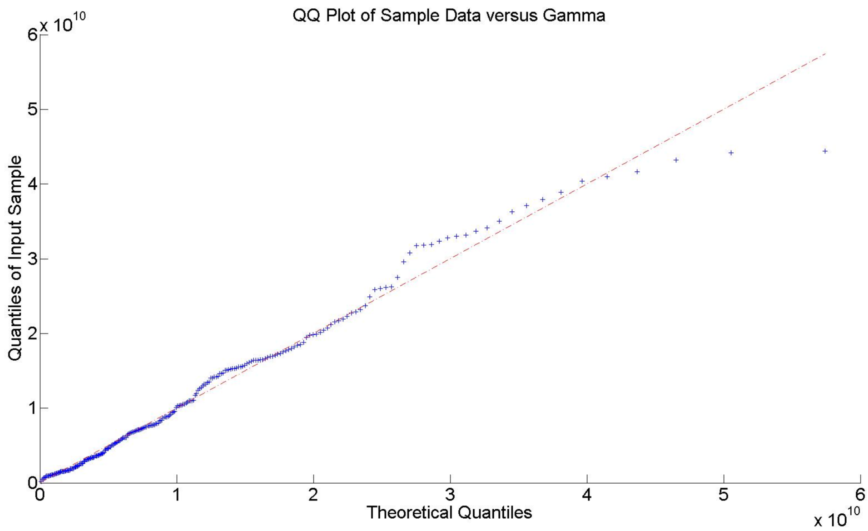

Figure 5.25: Gamma Distribution Compatibility with Large-scale Technology Data

It can be seen that the data from the large-scale modelling assumptions does not fit a normal or lognormal distribution (see Figures 5.22 and 5.23), but can be well characterised by weibull or gamma distributions (see Figures 5.24 and 5.25). The examples shown in these Figures consider data from the large-scale technology assumptions.

The gamma function can be characterised by two parameters, α (shape) and β (scale) (Nagaraja, 2006), and the gamma distribution has been selected as a suitable distribution for modelling the probability density functions of learning investment and total investment. Further information on the gamma distribution is available in the literature (Thom, 1958; Weisstein, 2015; Navidi, 2011; Nagaraja, 2006).

MATLAB allows for calculation of appropriate shape and scale parameters for a given distribution through the “gamfit” function, thus enabling convenient calculation of relevant shape and scale parameters for calculated learning investment and total investment datasets.

5.9.3 Outputs of the Stochastic Model

The outputs of the model are listed below:

- A database of technology cost reduction trajectories for each simulation;
- statistical values for learning investment (the maximum, minimum, mode and mean learning investment values, together with standard deviation);
- statistical values for total investment (the maximum, minimum, mode and mean learning investment values, together with standard deviation); and
- graphical outputs of: Cumulative Distribution Function (CDF); Probability Density Function (PDF); Frequency Occurrence Histograms.

The Monte Carlo simulation code was adjusted to represent either large-scale or small-scale technology development by changing the capacity of individual units from 1MW (large) to 100kW (small).

5.9.4 Testing the Model

The Monte Carlo simulation model allows the user to define the number of simulations to be carried out each time the code is run. While larger numbers of simulations may, to a point, improve the accuracy of the results, it was found that extending the number of simulations beyond a certain level increased computation time without providing significant impact to the overall result (see Figure 5.26). Monte Carlo simulations are, by their very nature, random tests, but we must ensure that the output results for the analysis do not deviate wildly between subsequent runs of the model, so that model outputs can allow for robust conclusions and arguments to be made. Within this research 250 simulations were selected for each run of the code to test the output, as this offered a balance between rapid computational time and ability to produce high fidelity PDFs. Ten model runs of 250 simulations each were carried out to test the model.

Each time the analysis was run, maximum, minimum, mean, median, mode, and standard

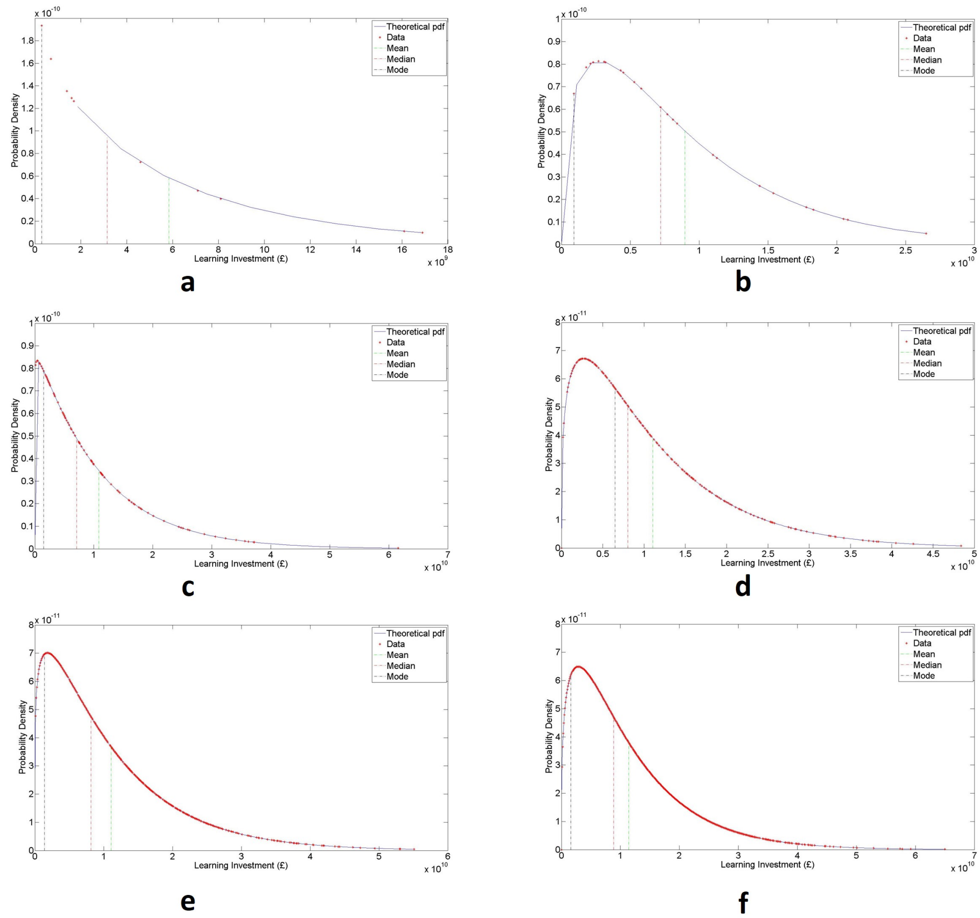

Figure 5.26: Effect of Changing the Number of Simulations on PDF Characterisation. a = 10, b = 25, c = 100, d = 250, e = 1000, f = 2500

deviation are calculated for learning investment and total investment from the results of the 250 scenario simulations. The modelled data allows for a number of output graphs to be generated.

The initial results of the Monte Carlo simulations analysed herein will be based on ten runs of 250 simulations for large-scale and for small-scale technologies, the results of which are found in Appendices B and C.

Test Results – Large Scale

Initial results of the Monte Carlo simulations suggest that for large scale technology under the input assumption conditions, the learning investment could range from £100 million to £63.3 billion – a large uncertainty which exemplifies the level of impact that minor perturbations to input parameters can have on overall investment requirements. The mean learning investment falls in the region of £11-12 billion, and the median in the range of approximately £8-10 billion. The relative stability of the output results despite the random nature of the input parameters confirms the model is performing consistently.

On initial observation, the CDFs from each analysis run suggest that, under our input assumptions, there is a 50% probability that the learning investment will exceed £10 billion. The minimum, maximum, mean, median, and mode learning investment from each large-scale technology modelling run are summarised in Table 5.8

The learning investment for gas turbine technology has been estimated as approximately $5 billion, using data from one major OEM – General Electric (Grubler *et al.*, 1999; MacGregor *et al.*, 1991). Based upon the input parameters and scenarios considered herein, the learning investment for MW-scale wave and tidal energy technologies could be significantly higher than that of gas turbine technology (which found extensive markets in civil and military transport in addition to energy sector applications).

Modelling Run	**Minimum Learning Investment) (£bn)**	**Maximum Learning Investment (£bn)**	**Mean Learning Investment (£bn)**	**Median Learning) Investment (£bn)**	**Mode Learning Investment (£bn)**
1	0.1	44.6	11.5	7.9	1.5
2	0.3	56.6	12.0	8.7	1.1
3	0.2	56.5	11.5	8.7	1.6
4	0.5	41.7	11.8	10.1	3.9
5	0.1	58.0	11.6	8.8	0.7
6	0.3	43.5	11.5	9.4	1.3
7	0.2	43.6	11.4	9.4	2.3
8	0.1	56.4	11.6	9.5	3.8
9	0.2	47.6	11.4	8.3	1.9
10	0.3	63.3	11.8	9.1	5.8
Average	**0.23**	**51.18**	**11.61**	**8.99**	**2.39**

Table 5.8: Monte Carlo Simulation: Results of 10 modelling runs of 250 simulations each (Large Scale).

5.9.5 Test Results – Small Scale

Results of the Monte Carlo simulations suggest that for small scale technology, the learning investment could range from a negligible value (the cost reduction occurs so rapidly that cost competitiveness with offshore wind is reached within such a small investment it is rounded down to zero) to £12.8 billion. The mean learning investment falls in the region of £2.4-2.8 billion, and the median in the range of approximately £2.0-2.6 billion, a significant reduction on the range – and uncertainty – associated with large scale technology. The relative stability of the output results despite the random nature of the input parameters again confirms the model is performing consistently.

On initial observation, the CDFs from each analysis run suggest that, under our input assumptions, there is a 50% probability that the learning investment for small scale technology will exceed £2.4 billion. The minimum, maximum, mean, median, and mode learning investment from each small-scale technology modelling run are summarised in Table 5.9

The results imply an increased attractiveness in the deployment of small scale technology, although it should be made clear that this result does not imply that the overall lifecycle cost or LCOE for small-scale technology would also have an observed increase in attractiveness over large-scale, as this has been a CAPEX only study. It is clear, however, that under unfavourable conditions (for example high SC, low LR, high CSCR), the learning investment uncertainty and overall cost is significantly reduced, which should be considered as more attractive for formative phase development and deployment.

It was expected that the small-scale technology results could demonstrate lower total investments and learning investments than the large scale technology results, given the omission of OPEX costs. However, the aim of this research was to demonstrate the magnitude of the impact on learning investment and total investment based on small changes to input parameters. In particular, the magnitude of the maximum possible learning investments due to unfavourable input parameters is significantly more severe in the case of large scale technology deployment than for small scale technology deployment, and is an issue irrespective of OPEX costs.

Modelling Run	Minimum Learning Investment) (£bn)	Maximum Learning Investment (£bn)	Mean Learning Investment (£bn)	Median Learning) Investment (£bn)	Mode Learning Investment (£bn)
1	0.1	9.4	2.6	2.5	3.1
2	0.1	8.1	2.5	2.3	2.3
3	0.1	8.1	2.7	2.5	1.5
4	0.2	9.7	2.8	2.5	2.0
5	0.1	9.8	2.4	2.0	1.7
6	0.1	10.8	2.7	2.6	1.6
7	0.1	12.8	2.6	2.4	1.5
8	0	10.7	2.6	2.4	0.4
9	0	7.8	2.7	2.5	1.0
10	0	10.8	2.6	2.3	2.0
Average	**0.08**	**9.8**	**2.62**	**2.4**	**1.71**

Table 5.9: Monte Carlo Simulation: Results of 10 modelling runs of 250 simulations each (Small Scale).

5.10 Monte Carlo Simulations – Formative Phase (First 1,000 Unit Deployments)

Chapter 4 of this thesis stressed the need to consider a formative phase of technology development. It is therefore useful in the context of this chapter to consider the economic uncertainty associated with formative phase development – particularly in terms of unit scale. Because it is highly unlikely that technology will be in a position to reach cost competitiveness with current offshore wind costs, except under extremely optimistic scenarios, it was necessary to consider the formative phase.

Prior work within this chapter has assumed a development trajectory consisting of 10,000 unit deployments. Under certain scenarios, cost competitiveness with offshore wind energy is not reached, however, a failure to reach cost competitiveness with offshore wind could dilute the appetite for further investment in ocean energy technologies. In reality, the cost of unit iteration and technology deployment could curtail the level of deployment far before 10,000 unit deployments are reached if significant cost reduction is not realised.

In the context of previous chapters of this thesis, a formative stage of development should be considered as an essential step on the route to product commercialisation – prior to unit and industry level up-scaling. The formative phase of technological development within a number of other energy sector technologies was considered (see Chapter 4): Steam turbines 799 units;

gas turbines 759 units; wind turbines 3,636 units; solar PV 460 arrays.

If we can consider the first 1,000 unit deployments to represent a plausible formative phase for wave and tidal stream energy technology development, then it would be of interest to compare both learning investment and total investment costs for large-scale and small-scale technology deployment.

The model was adjusted appropriately to limit the deployment to 1,000 units, and investigative analysis was carried out through Monte Carlo simulation of 1,000 unit deployments. The simulations were programmed to select 5,000 scenario possibilities. The results are shown in Table 5.10.

Unit Scale	Mean Learning Investment (£bn)	Median Learning Investment (£bn)	Mean Total Investment (£bn)	Median Total Investment (£bn)
Large	2.7	2.76	5.52	5.5
Small	0.5	0.5	0.78	0.78

Table 5.10: Monte Carlo Simulation: Results of modelling runs of 5,000 simulations of 1,000 unit deployments for large and small-scale technology.

Analysis has suggested that use of small scale technology could result in an 86% reduction in total investment costs and an 83% reduction in learning investment for a 1,000 unit formative phase. The resultant deployed capacity will be an order of magnitude lower using small capacity units, however, this should not be seen as a disadvantage during a formative phase of technology development.

The intention of the formative phase is to allow knowledge development through experimentation and iteration, and deployment of a large number of units (Grubler *et al.*, 2014). The costs associated with iteration and experimentation at large-scale is a significant barrier to deployment, which has been identified as economically unsustainable within this analysis. Small-scale modular technologies with lower capital requirements per deployment of technology offer a more granular approach to technology development that mitigates technological and economic innovation risks.

5.11 Monte Carlo Simulations – Final Model Run and Summary of Results

The final model run for each technology scenario involved 5,000 simulations. The results of this analysis are documented in Tables 5.11 and 5.12. Median, mean and standard deviation values are in £billion.

Technology Scenario	Std Dev. (σ)	Mean (μ)	Median	α	β	P_{10}	P_{50}	P_{90}
Large-scale	10.36	11.52	8.35	1.24	$9.32x10^9$	1.5	8.35	26.1
Large scale Formative	1.15	2.76	2.7	5.78	$4.78x10^8$	1.3	2.7	4.3
Small-scale	1.65	2.58	2.4	2.46	$1.05x10^9$	0.6	2.4	4.8
Small scale Formative	0.17	0.5	0.5	7.17	$6.98x10^7$	0.29	0.5	0.73

Table 5.11: Monte Carlo Simulation – Summary of Learning Investment Results.

Technology Scenario	Std Dev. (σ)	Mean (μ)	Median	α	β	P_{10}	P_{50}	P_{90}
Large-scale	18.05	32.37	36.3	3.22	$1.01x10^{10}$	6.8	36.3	54.1
Large scale Formative	1.24	5.52	5.5	19.93	$2.77x10^8$	4.1	5.5	7.1
Small-scale	1.99	5.17	5.2	6.74	$7.68x10^8$	2.4	5.2	7.6
Small scale Formative	0.17	0.78	0.78	18.84	$4.14x10^7$	0.57	0.78	1.01

Table 5.12: Monte Carlo Simulation – Summary of Total Investment Results.

5.11.1 Learning Investment

These results demonstrate that large scale technology deployment has a 90% probability of resulting in a learning investment of less than £26.1 billion, a 50% probability of resulting in a learning investment of less than £8.35 billion, and a 10% probability of resulting in a learning investment of less than £1.5 billion. Small scale technology deployment has a 90% probability of resulting in a learning investment of less than £4.8 billion, a 50% probability of resulting in a learning investment of less than £2.4 billion, and a 10% probability of resulting in a learning investment of less than £0.6 billion.

While £2.7 billion may seem an achievable sum for a formative phase deployment of 1,000 devices, the fact that wave and tidal stream energy technology is yet to prove cost-effective long term operational reliability and survivability should caution over-optimistic progression down this large-scale technology trajectory. It should also be noted that within the formative phase of deployment it is unlikely that unit costs will be reaching cost competitiveness with offshore wind, and much cost reduction could still be necessary.

Comparator results show that a formative phase of technology development (1,000 unit deployments) utilising small scale technology will have a 90% probability of achieving a learning investment of less than £730 million. This contrasts to large scale technology, in which there is only a 10% probability that the learning investment will be less than £1.3 billion.

5.11.2 Total Investment

Again, comparison of large and small scale technologies side by side allows the magnitude of investment to be put into context. The total investment uncertainties for large scale technology deployment result in plausible total investment costs that dwarf the total investment costs associated with small-scale technology by a factor of 6.

These results demonstrate that large scale technology deployment has a 90% probability of resulting in a total investment of less than £54.1 billion, a 50% probability of resulting in a total investment of less than £36.3 billion, and a 10% probability of resulting in a total investment of less than £6.8 billion. Small scale technology deployment has a 90% probability of resulting in a total investment of less than £7.6 billion, a 50% probability of resulting in a total investment of less than £5.2 billion, and a 10% probability of resulting in a total investment of less than £2.4 billion.

The results show that a technology deployment of 10,000 unit deployments utilising small scale technology will have a 90% probability of achieving a total investment of less than £7.6 billion. This contrasts to large scale technology, in which there is only a 10% probability that the total investment will be less than £6.8 billion.

Figure 5.27 indicates the learning investment (top left and bottom left) and the total investment (top right and bottom right) for 10,000 unit deployments (top) and 1,000 unit deployments (bottom) using large-scale technology. It should be noted that, although similar in appearance, there is an order of magnitude in difference between the x-axis of the large and small-scale charts.

Figure 5.28 indicates the learning investment (top left and bottom left) and the total investment

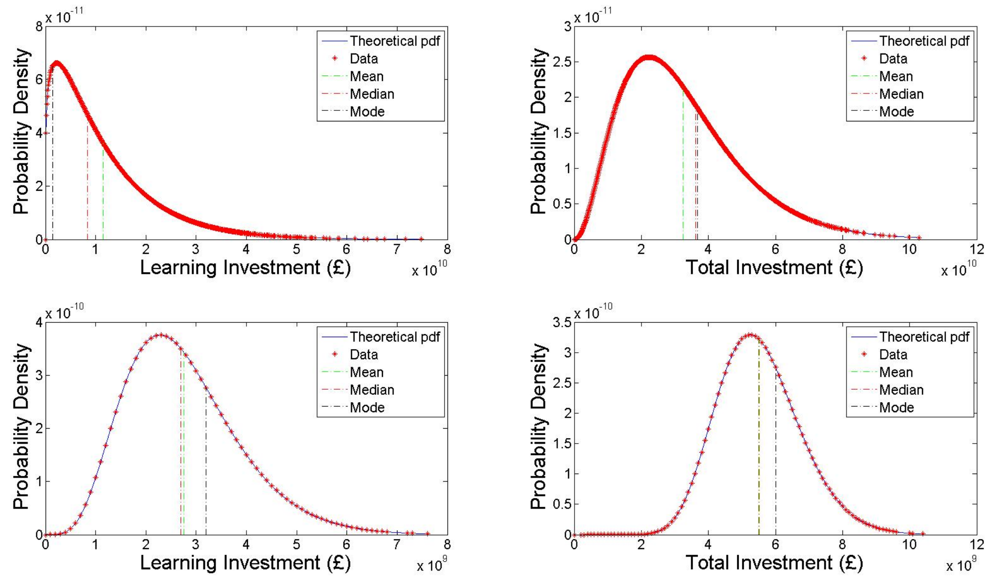

Figure 5.27: PDFs for 10,000 Large-Scale Unit Deployments (Top) and 1,000 Large-Scale Unit Deployments (Bottom)

(top right and bottom right) for 10,000 unit deployments (top) and 1,000 unit deployments (bottom) using small-scale technology. It should again be noted that, although similar in appearance, there is an order of magnitude in difference between the x-axis of the large and small-scale charts.

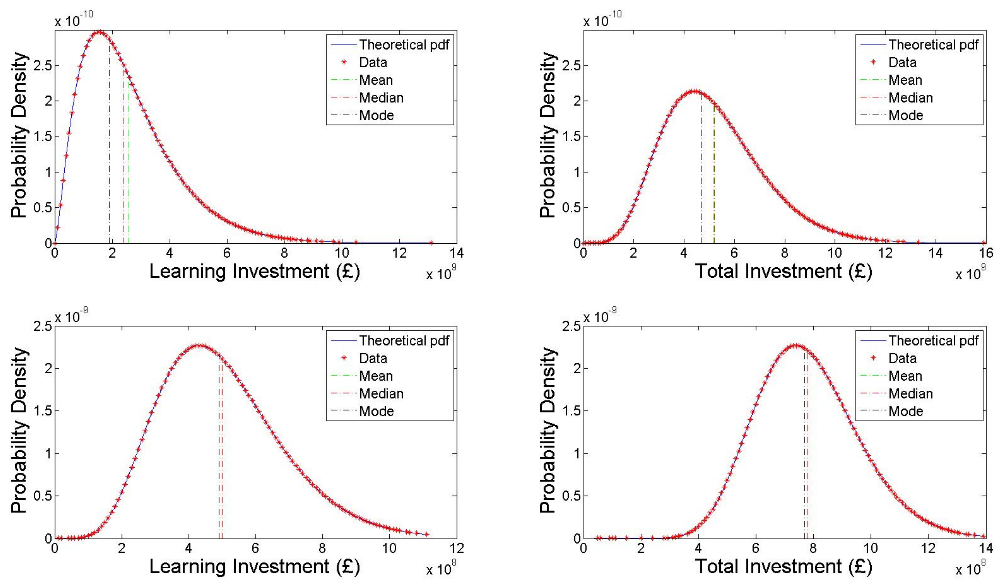

Figure 5.28: PDFs for 10,000 Small-Scale Unit Deployments (Top) and 1,000 Small-Scale Unit Deployments (Bottom)

5.12 Regional, National, and International Collaboration Scenario

The magnitude of the learning investment and total investment (and associated uncertainties) present a significant barrier to deployment for wave and tidal energy technologies. The level of economic risk that this presents is more than one single economy would be willing to commit to. Realistically, the ocean energy sector will require international collaboration in order to unlock the required funding and levels of deployment considered within this chapter.

In order to present the implications of this work for ocean energy research and development funding, it is prudent to first identify a favourable cost reduction scenario that is realistic in terms of both its optimism and achievability. The learning investment, and the underpinning starting assumptions that could lead to this learning investment are outlined. This will be presented for both large-scale and then small-scale technology. Implications will then be discussed.

5.12.1 Large-scale Technology

The median and mean value of learning investment from the simulations carried out in this work suggest that large scale technology development has a high probability of requiring a learning investment in the order of £10 billion. While a number of scenarios may lead to a learning investment in this region, this section will focus on a particular scenario that will be based upon the first ocean energy array project CAPEX costs, and a learning rate of 12% (as this value has been assumed within marine industry reports, and is close to the 11% learning rate achieved by wind energy (Junginger *et al.*, 2010b)), in which, according to the model produced within this work, a CSCR of 40MW (40 devices) must be realised in order to keep the learning investment below £10 billion. The assumptions are:

- A starting cost of £8,500/kW (MeyGen, 2015);
- A learning rate of 12% (Carbon Trust, 2011); and
- A 40MW capacity before sustained cost reduction consisting of 40 unit deployments

These assumptions, and the associated justifications, while perhaps a more credible cost reduction trajectory than that which has been assumed within ocean energy sector reports to date, still require optimistic low deployment prior to achieving sustained cost reduction.

The wind energy sector saw over 100MW of deployment (a deployment of around 1,400 units) prior to achieving minor cost reduction, and in excess of 800MW to achieve continuous and sustained cost reduction. It should be recognised that ocean energy technologies will not be permitted similar levels of deployment to the wind energy sector without demonstrating significant cost reduction, and an altogether more rapid cost reduction trajectory will be required if the ocean energy sector learning investment is to remain within affordable boundaries.

If deployment of a cumulative 200 megawatt-scale devices (across the sector – and not specific to one technology developer) is required in order to achieve sustained cost reduction, and the learning rate is maintained at 12%, then the starting cost will need to reduce to £6,400/kW in order for the learning investment to remain below £10 billion. In other words, a slight increase in the number of deployments prior to sustained cost reduction being achieved will require a large decrease in CAPEX cost in order to maintain a learning investment within the defined parameter.

In order to achieve this required starting cost, an increase in R&D funding will be essential, as cost reduction of this magnitude (a 25% reduction in CAPEX compared to existing costs) will require extensive research and development investigating innovative solutions prior to a focus on commercial array deployment. If the starting cost of technology remains much above this level, then it is highly unlikely that learning by doing cost reduction effects will allow a meaningful level of cost reduction to be reached in the medium term within an affordable learning investment.

It should be borne in mind that a learning investment in the order of £10 billion may not economically viable for one country alone for the development of a single technology. Given that the UK's annual R&D budget for 2014 (across the entire field of R&D activity) stood at £30 billion, it may conceivably be suggested that the UK alone cannot underwrite the costs associated with research, development and deployment of ocean energy technology to ensure it reaches a level of cost competitiveness with alternative technologies.

5.12.2 Small-scale Technology

The median and mean value of learning investment from the simulations carried out in this work suggest that small scale technology development has a high probability of requiring a learning investment in the order of £2.8 billion. While a number of scenarios may lead to a learning investment in this region, our identified scenario will be based upon a conceptual ocean energy array project CAPEX costs with a learning rate of 12%, in which, according to the model produced within this work, a CSCR of 14MW (140 devices) must be realised in order to keep the learning investment below £10 billion. The assumptions were:

- A starting cost of £10,000/kW; (Personal Communication, 2014)
- A learning rate of 12%; and
- A 14MW capacity before sustained cost reduction consisting of 140 unit deployments

These assumptions, and the associated justifications, still require a relatively low deployment prior to achieving sustained cost reduction in comparison to what was achieved in the wind energy sector.

If deployment of a cumulative 200 devices (across the sector – and not specific to one technology developer) is required in order to achieve sustained cost reduction, and the learning rate is maintained at 12%, then the starting cost will need to reduce to £9,250/kW in order for the learning investment to remain below £2.8 billion. As before, if the starting cost of technology remains above this level, then it is highly unlikely that learning by doing cost reduction effects will allow a meaningful level of cost reduction to be reached within an adequate deployment trajectory.

A learning investment in the order of £2.8 billion, while perhaps more palatable than the £10 billion associated with large-scale technology deployment, is perhaps still not something that can be considered economically viable for once country alone within a short to medium term time frame. Although offering some significant attraction over a large-scale deployment trajectory, utilisation of small-scale technology will still require international collaboration between leading actors in the field of ocean energy in order to secure successful technology development and commercialisation.

5.13 Economic Conclusion

Learning investment and total investment uncertainties have been largely ignored by industry reports, which ostensibly focus on 'probable' cost reduction trajectories without presenting the implications of minor deviations from optimistic innovation pathways.

The sensitivity of marine energy learning investment to a number of parameters has been comprehensively demonstrated in this section. The results have drawn attention to the overall levels of investment cost sensitivity to key input assumptions (SC; LR; CSCR), and the resultant learning investment uncertainty. This is a particularly important consideration given that the parameter ranges used within this analysis for SC and LR are often used within the marine energy sector, but without reference to the impact on overall learning investment, which provides a more realistic assessment of the overall levels of support required in order to reach commercially attractive wave and tidal energy sectors.

The uncertainties in key parameters affecting learning investment have the potential to 'make or break' the wave and tidal energy industries. Overall, the analysis found total learning investment costs ranging from modest sums (tens of millions) under attractive assumptions, to financially and politically infeasible levels (tens of billions) under certain scenarios. Under parameter range variations described within this section, the risk and uncertainty associated with this large financial investment, under current large-scale technology deployment trajectory, makes ocean energy development and deployment a highly undesirable prospect from the perspective of a private sector investor. This research has presented that a MW-focused deployment trajectory is not the most economically sustainable development environment – large investment costs are needed to realise each iteration and unit deployment, and optimistic deployment and cost reduction trajectories are needed if financially feasible learning investments are to be realised.

For the first ocean energy arrays, a large percentage of the total cost is provided through public sector funding, but this is unlikely to continue in the longer term – certainly at the level seen to date. If optimistic deployment and cost reduction trajectories are not achieved, then ocean energy technology will struggle to raise sufficient capital to finance continued deployment. Early cost reduction was anticipated within the offshore wind energy sector but did not materialise. There is little opportunity to repeat this trend. The marine energy sector cannot afford to make cost reduction promises that it may not be able to fulfill, as the investment community may not have the patience to remain committed for substantial levels of deployment prior to achieving sustained cost reduction.

By shifting the focus of development and deployment towards small-scale units, each iteration or deployment can take place at a significantly reduced cost, allowing for a larger number of deployments to take place within a given total investment – and the opportunity to realise significantly reduced learning investments within a formative phase.

Probabilistic modelling of the learning investment yields several interesting comparisons between the learning and total investment costs for small scale and large scale technology development and deployment. Due to the level of uncertainty in input parameters, the investment costs associated with large-scale technology deployment make a very unattractive case. However, there is opportunity to significantly reduce the economic uncertainty (particularly regarding formative phase technology development) if a small-scale technology trajectory is followed.

Focusing specifically on the first 1,000 unit deployments – representative of a formative phase of technology development – reveals the lower risk alternative available through development and deployment of smaller scale technology at the outset. Larger levels of unit deployment at smaller unit capacities would present a more efficient use of available funding, and could lead to a more economically sustainable research, development and innovation environment for wave and tidal stream energy technologies. Until wave and tidal energy technology has successfully demonstrated a formative phase of development, the opportunity to iterate and prove performance at a lower unit cost (and lower overall learning investment) should not be overlooked.

The economic analysis within this work has clearly demonstrated the cost-effectiveness of small scale technology – in terms of reducing the economic risk associated with development and deployment. By reducing the unit iteration and deployment costs through implementation of small-scale technology rather than a focus on mass-production of large capacity units, more cost-effective iteration and deployment steps are facilitated. The associated costs of formative phase development are likely to be significantly lower by following a small-scale unit development and deployment trajectory, in spite of a what may currently be a larger initial capital cost-per-kilowatt.

It should be remembered that OPEX was not included within this study. The inclusion of robust values of OPEX, when the information becomes available through operational experience, could have a substantial impact on the outcome of this section.

Chapter 6

Analysis of Policy Support for Innovation in the Wave and Tidal Energy Sectors

6.1 Chapter Introduction

There is no doubt that implementing the appropriate policy frameworks and support mechanisms for encouraging growth and innovation can be a great challenge, particularly in the case of radical or disruptive technologies (Michalena and Hills, 2013). The high technological and economic risk associated with innovation can require a steering hand from suitable policy and support mechanisms in order to facilitate a transition from invention through to diffusion of technology. In most industries, a technology generally becomes established when the private sector becomes actively involved, and sustains its involvement. Until such a time, public sector funding is necessary to propagate technology development. This funding needs to be utilised wisely if it is to foster the emergence of a successful ocean energy sector.

On one hand, there is widespread recognition that apposite socio-political support brings benefit to the development of renewable energy technologies – indeed the emergence of wind energy technology in Denmark in the 1970s and 80s is a prime example of where successful technology diffusion has emerged within a positive enforcing socio-political context (Valentine, 2015). On the other hand, inappropriately directed, rapidly fluctuating or ill-defined policy support mechanisms run the risk of adversely altering the profile of formative innovation activity entirely.

Policies supporting accelerated energy innovation and large-scale deployment of technologies have been experienced in the case of the UK energy sector, where large-scale system change is necessary within the electricity network and power generating assets. However, the rise of accelerated energy innovation is an impediment to niche led innovation, which can contribute to more disruptive changes in the innovation process (Winskel and Radcliffe, 2014). While perhaps desirable in encouraging short term objectives and targets to be met, this accelerated energy innovation environment could become a stumbling block to the very innovations which are required in order to bring about radical change.

Policies have perhaps made premature or incorrect judgements in terms of the appropriate support mechanism to foster deployment growth in the wave and tidal energy sectors, as the levels of growth envisaged by early sector pioneers has failed to materialise (Vantoch-Wood, 2012b,a). However, until recently, the last decade would appear to have been considered auspicious times for the wave and tidal energy sector (Mccullen *et al.*, 2002; Vantoch-Wood, 2012c). The failure of technology development to reach levels of availability, survivability, affordability, and performance that are of interest in stimulating private sector investment has resulted in a stagnation in private sector development and deployment activity within both wave and tidal energy sectors within the UK – perhaps presented most clearly in the entering into administration of Pelamis Wave Power, which had been considered as one of the UK's leading developers of wave energy technology (Vantoch-Wood, 2012c), and that of Aquamarine Power during 2015.

This chapter is about comparing the policy landscape of a mature renewable energy technology with that of a new and emerging technology – with a particular focus on the balance between technology push and demand pull support mechanisms during the early phases of technology adoption. This was carried out through a case study involving onshore wind in Denmark to represent the mature renewable energy technology, and wave and tidal energy in the UK to represent the new and emerging technology. It was anticipated that specific investigation in key metrics would reveal several underlying influences that can be considered as reliable indicators of technology readiness for transition from technology push to market pull support mechanisms.

Six metrics have been identified in Table 6.1 and are used as a means of comparison of technology maturity between the onshore wind energy sector and emerging ocean energy technologies. Timescales associated with significant events within each of the metrics are used as a proxy in which to assess the suitability of transition from technology-push to demand-pull mechanisms. The six metrics were identified through a modified version of the PESTLE (Political, Economic, Social, Technological, Legal and Environmental) analysis, which focused predominantly on the techno-economic themes. The list of possible metrics has not been exhausted, but the chosen metrics were selected for their importance within the formative phase of technology development.

6.2 Policy Transition – Technology-push to Demand-pull

Ocean energy technology development has focused on MW-scale technology, but the justification for policies supporting this 'accelerated innovation' development pathway remains unclear from a technological perspective – the direction appears to be driven by an economically focused argument, in particular return on investment through rewarding production rather than the apposite demonstration of reliable and robust technologies. Current policy support has not enabled the development of a successful technology suitable for commercialisation and existing policies within the UK wave and tidal energy sector are leaning heavily towards demand-pull mechanisms.

The Danish government understood the market dynamics surrounding the development of the wind energy sector and made pertinent responses that fitted with the needs of industry stakeholders (Valentine, 2015). It is for this reason that this the policy focus of this research was envisioned as a comparison of the Danish wind energy sector and the UK wave and tidal energy sectors, concerning the position of technology development with respect to a transition from technology-push to demand-pull dominated support mechanisms.

An approach used regularly over the last decade to analyse an organisation or industry is the PESTLE analysis. The PESTLE analysis is a strategic tool used to assess the state of an organisation or industry in terms of its current position, growth potential and direction, with the purpose of using the findings of the analysis to guide strategic planning and decision-making. PESTLE (or PEST/STEP) analysis is a proven technique and one that is used for a variety of applications, and it is particularly useful when trying to understand the 'bigger picture' of the environment in which an industry is operating.

However, there are certain areas of the PESTLE analysis that are beyond to the needs and requirements of this thesis, and distract the focus from the core aim of the policy investigation; therefore this study used a modified version of a PESTLE analysis that focused specifically on the core "economic" and "technological", themes. This resulted in the examination and implementation of metrics that investigated the techno-economic performance of wind, wave and tidal energy technologies across a range of criteria relative to policy implementation timelines.

Performance metrics are by definition parameters of quantitative assessment, with their use aimed at measuring, comparing, or tracking performance, making them an ideal tool to assess the maturity of an industry when applied appropriately. The policy focused study considers six metrics in which the Danish wind energy sector was deemed to be well established prior to the transition from technology-push to demand-pull dominated support mechanisms. The metrics are outlined in Table 6.1. Timelines, and identified points of interest, will be compared between wind energy and ocean energy for each metric to identify whether the transition from technology-push to demand-pull dominated support mechanisms within the wave and tidal energy sector in the UK have been premature.

6.2.1 Historical Periods Analysed

Modern Danish wind energy development evolved following the 1973 oil crisis; a socially driven impetus to move away from externally-influenced fossil fuel prices and a strong anti-nuclear public opinion allowed favourable conditions for wind technology to develop (Valentine, 2015). The Danish government implemented many of its support mechanisms for the wind energy sector over the following two decades, before embarking on a transition from technology-push to demand-pull focussed mechanisms. Although having a form of Feed-in-Tariff in place since 1979, Denmark adopted a principal demand-pull mechanism in the form of a consistent feed-in-tariff from 1998 (Neij *et al.*, 2003). The investment subsidy for wind turbines was removed completely at the end of 1989, and the transition point from technology push to market pull was set at 1990. Therefore a 30 year period between 1970 and 2000 was be used when analysing the Danish wind energy sector.

Development of wave and tidal energy technology within the UK was re-established in the mid-1990's, when several wave and tidal energy companies were established. The UK and Scottish governments have provided a number of funding opportunities for early stage development, in the form of both technology-push and demand-pull support, but limited deployment activity beyond single unit demonstrator prototypes has taken place.

The principal mechanism for supporting utility scale renewable energy development in the UK was through the Renewables Obligation and the issue of Renewables Obligation Certificates (ROCs). ROCs are certificates issued to the operators of accredited renewable generating stations for the eligible renewable electricity that they generate. The operators can then trade

Identifier	Metric	Description	PESTLE Category
Metric 1	CAPEX Cost	The cost of units, in terms of both cost/kW and total CAPEX cost.	Economic
Metric 2	Research and Testing	The establishment and the geographic dispersion of test facilities, and the coordination between test facilities and industrial development. This metric also considers appropriate capture and curation of knowledge.	Technological
Metric 3	Technology Development and Diffusion	Linking the technology scale and number of units deployed as indicators of commercial readiness and level of diffusion into a market.	Technological
Metric 4	Design Consensus	Emergence of dominant designs and front-running technology. Attrition of non-optimal solutions.	Technological
Metric 5	Certification	The assessment of how well a technology meets the demands and requirements placed upon it, and confirmation that the technology meets intended objectives. The certification process must be officially recognised if it is to be credible in its influence on technology development.	Technological
Metric 6	Experienced Developers	The assessment of the number of experienced technology developers present within the research, development and innovation environment, a proxy indicator of technology maturity.	Technological

Table 6.1: Identified Metrics.

ROCs with other parties. The overall aim of ROC scheme is to demonstrate that a supplier has met their obligation to produce a required amount of electricity from renewable sources.

If a supplier was not able to present a sufficient number of ROCs to meet their obligation over the course of a one-year reporting period, then they must pay an equivalent amount to cover their shortfall into a buy-out fund.

The UK introduced its main demand-pull mechanism to support the marine energy sector in 2011 (Scotland) and 2012 (rest of the UK) by increasing the number of ROCs to 5 per MWh. The ROC was then expected to operate as the principal driver for stimulating further development in ocean energy technology. Therefore a 20 year period between 1995 and 2015 was used when analysing the UK marine energy sector.

6.3 Policy Support Mechanisms

A government or administrative body supporting a new technology in a given market can consider the use of mechanisms that fall, broadly speaking, in one of two categories: Technology-push or demand-pull. Technology-push focuses on the fundamental science and advancement in technology through research and development of new techniques that can enable a new product or service. Demand-pull focuses on the market for a given product or service – a demand for a particular product or service can stimulate development and diffusion of a successful product that meets this demand. Examples of technology-push and demand-pull support mechanisms can be found in Table 6.2.

Historically, there has been differing viewpoints on which of the methods offer the highest stimulus to technology development and innovation, with arguments providing advantages and disadvantages for both technology-push and demand-pull methods (Nemet, 2009).

In practice, both technology-push and demand-pull mechanisms are necessary to ensure the success of innovation. If technology-push mechanisms are withdrawn too early, then it is possible that the technology may not have reached sufficient levels of development or maturity, and will therefore be considered too high risk for private sector investment. If demand-pull mechanisms are introduced too early, then this could cause over-optimistic market conditions for an under-developed technology. However, if demand-pull mechanisms are not introduced early enough, there could be increased risk to the investor as a result of the length of time lag between initial investment and subsequent returns associated with successful commercial application – making the private sector reluctant to invest (Nemet, 2009). Therefore appropriately defined technology-push and demand-pull support mechanisms must exist simultaneously in order for a technology to develop to its full potential, however the contribution of each is difficult to define and often must be made on a case-by-case basis depending on the technology (Nemet, 2009; Mowery and Rosenberg, 1979).

Technology-Push	Demand-Pull
Mechanisms:	**Mechanisms:**
Capital investment subsidies to fund demonstration projects	Feed-in-Tariff
Dedicated research centre funding	Soft loans
Tax credits to stimulate R&D investment	Tax credits and rebates for consumers of new technologies
Government sponsored R&D programmes	Regulation of grid-connection
Certification incentives	Tradeable permits
Standardisation incentives	
Considerations:	**Considerations:**
Can be considered 'catalysing' approaches (Lund, 2007). Technology is 'pushed' through development – through the provision of dedicated funding to enable development to overcome specific identified challenges – to a stage of commercial readiness.	Considered to be most effective when directed at more mature technologies, where stimulation of volume production could be seen to drive cost reduction through economies of scale (Vantoch-Wood, 2012a).
Generally considered appropriate for technologies at nascent stages of development.	Generally ignores the technological readiness of the supported development for in-service application (Nemet, 2009).
Do not adequately reflect the opportunity for market conditions to influence technology development (Vantoch-Wood, 2012a).	

Table 6.2: Technology-Push and Demand-Pull support mechanisms.

6.3.1 Background Information

Policy Framework – UK and Scottish governments (marine)

Almost £185 million of public money had been targeted over a 10-year period towards wave and tidal energy by the UK government by the end of 2012 (Jeffrey *et al.*, 2014).

A number of programs administered by the Carbon Trust such as the Marine Renewables Deployment Fund (MRDF), Marine Renewables Proving Fund (MRPF), and Marine Renewables Commercialisation Fund (MRCF) have involved sizeable financial motivators, but the assessment of the success of these programs is subjective. The MRDF programme, established in 2004, was a failure – no technologies were deemed eligible to meet the entry requirements for the capital grants and revenue support offered by the termination of the scheme in 2011. The criteria for entry were strict, and technology developers were unable to meet the requirements to develop full scale (defined as MW-scale) prototypes suited to multiple device deployment within the time frame of the funding opportunity. However this is a reflection on the level of technology development, which was not at a stage to take advantage of a scheme designed to support pre-commercial array deployment – the scheme itself was well designed for its intended purpose, but was introduced prematurely, partly due to developer over-optimism in the sector (DECC, 2012).

The MRPF was introduced in 2009 to address the failures of MRDF to support technology development at an appropriate stage for the industry. For most, the MRPF scheme has largely been considered a success – six technologies were supported to deploy technology at full-scale. However, the supported technologies were all MW-class technologies, and recent industry trends have resulted in some uncertainty within the companies who were considered as 'leading' technology developers:

- Entering into administration of Pelamis Wave Power and Aquamarine Power;
- The divestment of Marine Current Turbines (MCT) from parent company Siemens. MCT was subsequently acquired by Atlantis Resources Corporation;
- Voith Hydro Ocean have divested their ocean energy technology development interests.

The remaining companies supported by MRPF, Atlantis Resources Corporation and Hammerfest Strom UK (now Andritz Hydro Hammerfest), are partners within the leading array development, MeyGen, in the north of Scotland, who will be attempting to deploy the first of four units during the fourth quarter of 2016.

More recently, the Marine Energy Array Demonstrator (MEAD) scheme was launched to support the first tidal energy arrays. With criteria placing an expectation on the delivery of 10GWh per year to the electricity grid, at least three generating devices, and a total capacity of 5MW or greater, the focus is again on large scale ocean energy technologies.

The above funding mechanisms demonstrate a clear impetus for large scale technology development – creating a demand for large scale technology and thus influencing the pathway of technology development to meet these goals.

One of the most significant policy support changes implemented by the UK government to date is the Renewables Obligation (RO) scheme. The RO scheme was introduced in 2002 in Scotland, England and Wales, followed by Northern Ireland in 2005 in order to ensure that an increasing proportion of electricity is generated from renewable sources. The scheme uses green certificates (known as ROCs) issued to operators of accredited renewable generating stations that can be traded among operators, as suppliers must demonstrate that they have met their obligation to help reduce carbon emissions. When a supplier does not have a sufficient number of ROCs to demonstrate that they have met their obligation, the penalty is a fee equivalent to the shortfall, which is paid into a buy-out fund. This fund is then distributed back to suppliers in proportion to the number of ROCs that have been produced (Ofgem, 2015). The RO is an effective long-term market signal that governments are committed to the development of a sector, providing confidence and certainty to stakeholders.

Recognising that not all renewable energy technologies are at an equal level of maturity, the idea of banding ROCs on the basis of technology type allowed for additional incentives to be provided to innovative technologies. After a review in 2011, the Scottish government announced that they would raise the wave and tidal ROC banding to 5 ROCs per MWh generated for projects up to a level of 30 MW installed capacity. That is, for every MWh generated by wave or tidal energy, the ROC payment would be five times that of wind (which received one ROC per MWh). This can be considered as the most significant demand-pull mechanism implemented by government, aimed at supporting development and deployment within the UK marine energy sector. Between April 2015 and March 2016, the buy-out price of one ROC was set by Ofgem at £44.33 per ROC.

Perhaps the most significant unknown for the UK's marine energy sector is the Electricity Market Reform (EMR) process which will be replacing the RO scheme in 2017 (DECC, 2013a). EMR will set an initial strike price of 305 £/MWh for both wave and tidal energy technologies, with the contract period set at 15 years (DECC, 2013b). There exists significant political uncertainty regarding the level of long term support and strike prices for marine energy technologies beyond 2020 (Jeffrey *et al.*, 2013).

Policy Framework – Danish government (wind)

The 1973 oil crisis gave rise to an ambition in Denmark to become independent of imported oil for energy production (Smith, 2011; International Renewable Energy Agency, 2013). High oil prices, and a rising anti-nuclear social movement led to the formation of the Danish government's wind power research program in 1975 (Nielsen *et al.*, 1998). The wind turbine movement was led through the grassroots development of small turbines, which allowed individual farmers or community cooperatives to take ownership of their turbine. Agricultural companies in Denmark, seeing the growth potential that wind power offered, began developing in-house wind turbines, which quickly established a good reputation for their reliability in the 1980s (Valentine, 2015).

The Danish government implemented a number of policies over a 20 year period between 1976 and 1996 that helped foster the growth and emergence of the wind energy sector (International Renewable Energy Agency, 2013). A number of these policies are listed below:

- Energy taxes on electricity prices in the mid-1970s, used to support R&D for renewable energy. This provided financial support for public research while spreading the cost of research among all electricity customers;
- Taxes on oil and coal energy plants. This helped to increase the competitiveness of renewable energy plants;
- Tax incentives offered to Danish communities for generating power for their communities;
- Prohibition of the development of nuclear energy plants from 1985;
- An agreement with utilities to develop 100 MW of wind power between 1986 and 1990, which supported the industry at a time when there was a decline in the wind turbine export market;
- Independent investors in wind turbines were offered priority access to the grid. Infrastructure improvements were put in place to enable additional capacity;
- Wind projects received a refund from the Danish carbon tax and a partial refund on the energy tax, which was equivalent to a two-fold rise in the payment to wind energy projects during the initial 5 years of operation.

Between 1980 and 2000 the Danish government spent approximately £800 million on market incentives and £120 million on R&D projects (Smith, 2011). The Danish wind energy sector's success benefited significantly from this early support of R&D. Although wind power policy in Denmark was often diverse and eclectic, the policy support mechanisms represented a disposition on the government's part to experiment with different policies in order to attain the most appropriate support to meet the needs of the stakeholders.

The investment subsidy schemes implemented by the Danish government between 1979 and 1989 played a critical role in establishing confidence in the market, and paved the way for rapid increases in cumulative installed capacity. The subsidy scheme initially offered 30% of the total investment cost for the installation of wind turbines that were approved by the Risø National Laboratory test station (Klaassen *et al.*, 2005). This scheme was gradually reduced to 25% in

1983, 15% in 1984, and then 10% in 1989, before it was withdrawn completely by the Danish government in 1990 (Meyer, 2007; Neij *et al.*, 2003). Together with a coordinated program of R&D support to the sector, the scheme resulted in the development of commercial technically reliable wind turbines by the end of the 1980s (Klaassen *et al.*, 2005). Given that the subsidy offset the capital costs of deploying wind turbine technology, this incentive scheme has been considered, for the purposes of this paper, to be a technology-push support mechanism. The transition in 1990 from investment subsidy (technology-push) to a demand-pull feed-in-tariff dominated support mechanism can be considered as the most significant transition in policy support for wind energy implemented by the Danish government.

6.4 Analysis

6.4.1 Metric 1 – CAPEX Cost

The cost of units in terms of both cost/kW and total CAPEX cost, represent important metric for observation. Opportunity exists to display demonstrable progress if costs/kW can be seen to reduce in line with increasing levels of deployment, however this cost decrease must be accompanied by evidence of reliable system performance. The total CAPEX costs, while less predictable in terms of what a market is willing to pay, perhaps offer an indicator of early stage development and innovation in terms of cost per unit iteration. A summary timeline for CAPEX cost milestones relative to the shift between technology-push and demand-pull support mechanisms, for both wind and marine energy sectors, is presented in Figure 6.1.

Wind

Wind turbine Capital Cost data is available within the literature for wind turbines manufactured and installed in Denmark (Neij *et al.*, 2003). The first three data points in the original data series reflect price increases (this is consistent with the “development” and “price umbrella” phases of market introduction of a new product, where price or cost reduction is unlikely to be manifest until a subsequent “shakeout” phase and further cumulative deployment, as described within the literature (Junginger *et al.*, 2010a)); the remaining data points represent sustained (although not a constant rate of) cost reduction.

For the purposes of evaluating this metric, the same cost data will be presented in four different ways, with a brief description of each related chart to highlight the important features of the

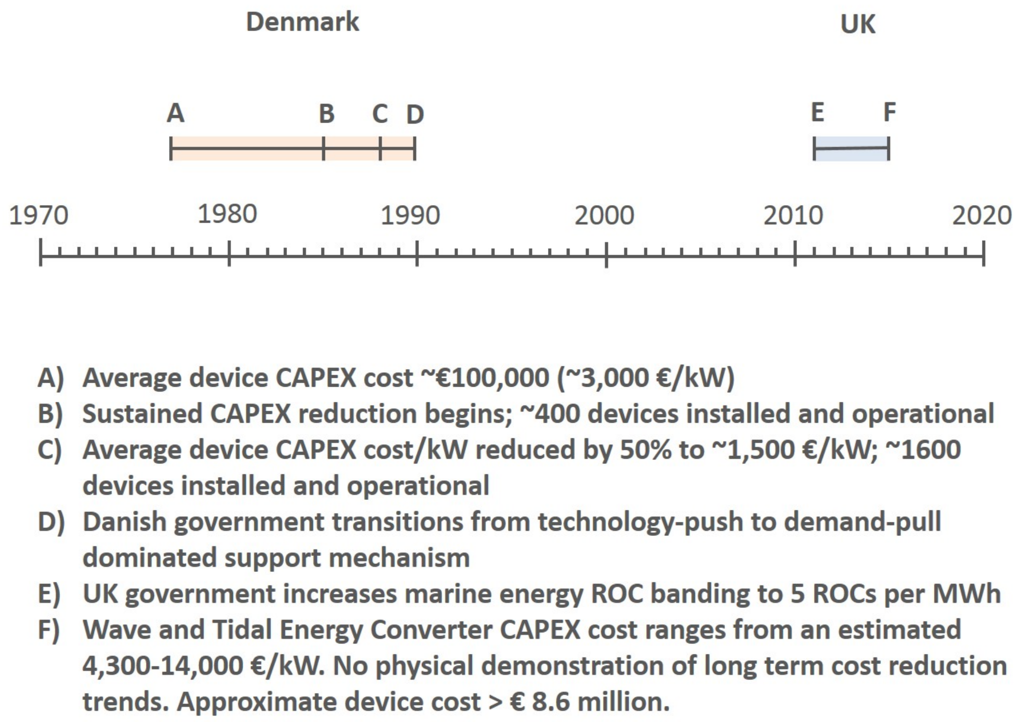

Figure 6.1: Timeline comparing the Danish wind and UK wave and tidal energy sectors in relation to CAPEX cost before the transition to demand-pull support mechanism.

graph. Four related charts will be presented: Figure 6.2, Figure 6.3, Figure 6.4, and Figure 6.5. Each chart is labeled a, b, c, and d respectively, but it should be noted that the same cost data is used as the basis for the plotting of each chart.

The cost model created for this chapter differs from that considered in Chapter 5, as it utilised existing cost data presented within existing research, in conjunction with the Danish Wind Turbine Master Register (Energi Styrelsen, 2014) to define the number of turbine unit deployments. From this register of wind turbines, the total cumulative deployed capacity was also calculated, allowing the Danish Wind Turbine Master Register to be cross correlated with cost data from existing wind turbine cost reduction research papers (Garrad, 2012; Neij *et al.*, 2003).

First, wind turbine cost data, taken from existing literature (Garrad, 2012; Neij *et al.*, 2003), was plotted on a log-log scale to observe overall cost reduction and learning trends. The learning curve research presented by Neij *et al.* (2003) uses cost data at levels of deployment from 10MW. However, the Garrad (2012) paper presents the cost of Bonus wind turbines dating back to 1980, with a starting cost of 3000 €/kW. For the purpose of this research, through comparison with the Danish Wind Turbine Master Register it was ascertained that the cumulative wind turbine deployed capacity in 1980 was approximately 1MW. For the purposes of this research, wind turbines deployed before 1980 were assumed to have a CAPEX cost equivalent to 3000 €/kW. This collated data, presented on a log-log scale, can be seen in Figure 6.2, which presents three distinct trends:

- An initial cost reduction phase exists between the early Bonus wind turbines, and those wind turbines deployed when the cumulative installed capacity was 10MW.
- Between 10MW and 20MW of cumulative deployed capacity, the cost of wind turbines was seen to increase very slightly – a price umbrella (as discussed in Chapter 5) – sustained cost reduction was not continuously experienced by the early wind energy sector.
- Beyond 20MW of cumulative wind turbine deployment, a sustained cost reduction trend was seen to emerge.

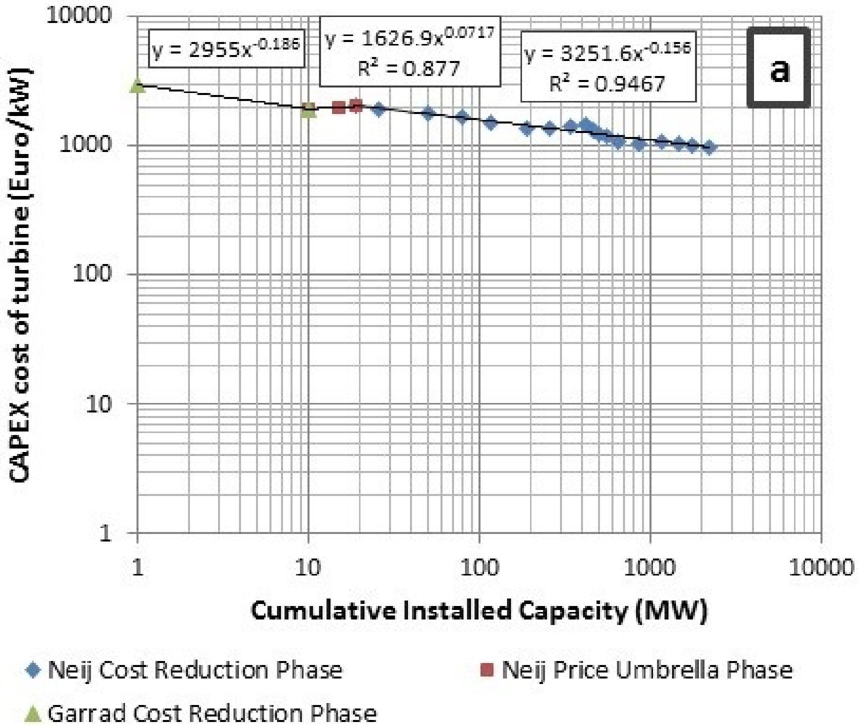

Figure 6.2: Wind turbine costs (price adjusted for inflation to 2015 prices), original dataset re plotted to 2015 price (a)

Revised trend lines were created for each of the above phases using the 'power' trend line function within Excel. This allowed the equation of each of the three trend lines to be explicitly identified.

In order to reflect the price of early wind turbine deployments within the model, the cost is assumed to linearly reduce from 2900 €/kW at 1MW cumulative deployment to approximately 1950 €/kW at 10MW cumulative deployed capacity – representing a period of transition between cost figures presented in Garrad (Garrad, 2012) and cost figures presented in Neij (Neij *et al.*, 2003). All turbine deployments prior to 1MW cumulative capacity have been assumed to remain constant at the cost associated with the 1MW data point.

Between 1981 and 1984, the CAPEX cost of a wind turbine, in terms of €/kW, rose. From 1985 (51MW cumulative deployed capacity) onwards, sustained cost reduction was once again achieved and by 1990 (345MW cumulative deployed capacity) CAPEX costs had fallen below approximately 1400 €/kW installed.

Costs for wind turbine deployments within each phase were then calculated by correlating the cumulative installed capacity from Figure 6.2 with the cumulative installed capacity in the Danish Wind Turbine Master Register and applied to a cost model that presents wind turbine cost relative to the number of turbine unit deployments or installation date, which allowed the creation of the graphs in Figure 6.3, Figure 6.4, and Figure 6.5. Figure 6.3 displays the CAPEX/kW cost trajectory with respect to time.

In order to plot the CAPEX cost of Danish wind turbines over increasing numbers of unit deployments, the original dataset had to be converted from cumulative installed capacity to time (based on the month/year of deployment within the Turbine Master Register and directly linked to cumulative deployed capacity), and then extracted on a turbine by turbine basis to get an approximate cost for individual unit iterations between 1977 and 2000. Figure 6.4 displays the CAPEX/kW cost trajectory with respect to the number of unit deployments.

If the CAPEX cost per kW is mapped on to the device capacity of each turbine at deployment, the total capital costs for the early Danish wind turbines can be approximated analytically, as demonstrated in Figure 6.5. This graphical depiction is in a different format, as it considers total CAPEX cost of a wind turbine, rather than presenting the data on a cost-per-kW basis. It highlights that although CAPEX costs decreased on a cost-per-kW basis, the total outlay for a wind turbine was lower in the initial stages of deployment. This could perhaps be considered instrumental in facilitating early adoption of technology within the first emerging markets.

Device CAPEX costs are initially modest, in the order of €100,000 per device. Although cost/kW represents a decreasing trend, the total device CAPEX is associated directly with

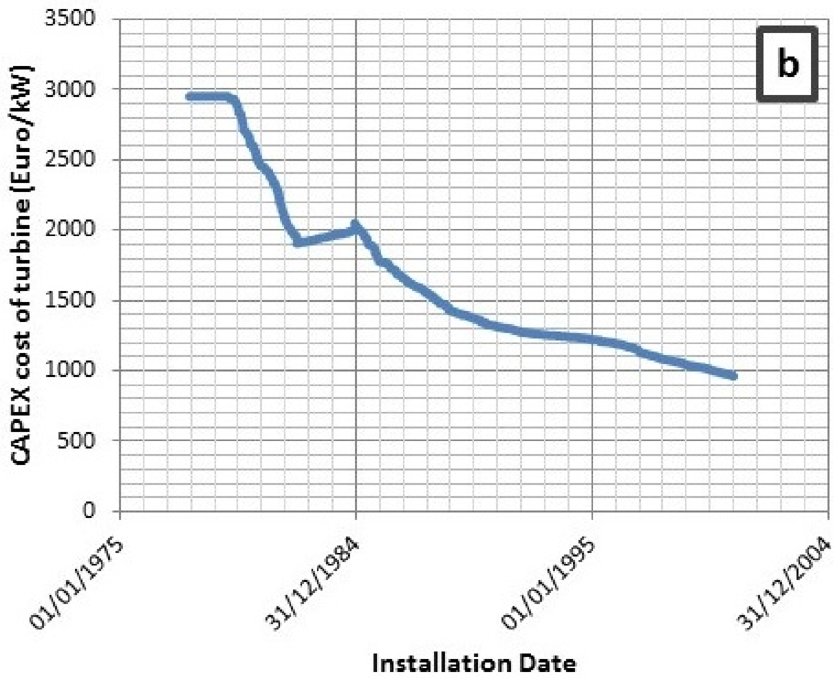

Figure 6.3: Wind turbine costs (price adjusted for inflation to 2015 prices), x-axis set as time (b)

the scale of the technology. Due to the increases in wind turbine scale, the trend line depicts an increasing total device CAPEX cost in line with increasing levels of deployment – clearly consistent with the growth in wind turbine capacity. However, it should be noted that by the time of the transition to a market pull orientated support mechanism, turbine unit costs can be approximated to be in the region of €300,000, and there were over 3,000 device deployments.

The wind energy sector in Denmark had therefore demonstrated sustained CAPEX cost/kW reduction for a period of 5 years prior to the transition to a market-pull dominated support mechanism. In addition, CAPEX cost/kW had reduced by 65% from its initial value prior to the Danish government's transition to a market-pull dominated support mechanism.

It should be noted that with increasing levels of deployment experience, the total CAPEX expenditure on wind turbines was seen to increase; as technology scale increases the overall unit cost increases correspondingly. The increase in CAPEX represents a willingness for investors and developers to progress to larger technologies, due to confidence obtained from previous iterations of device. However, up until the year 1990, only approximately 9 turbines incurred a CAPEX cost of greater than €1 million (approximately 0.4% of the data range). The cost of

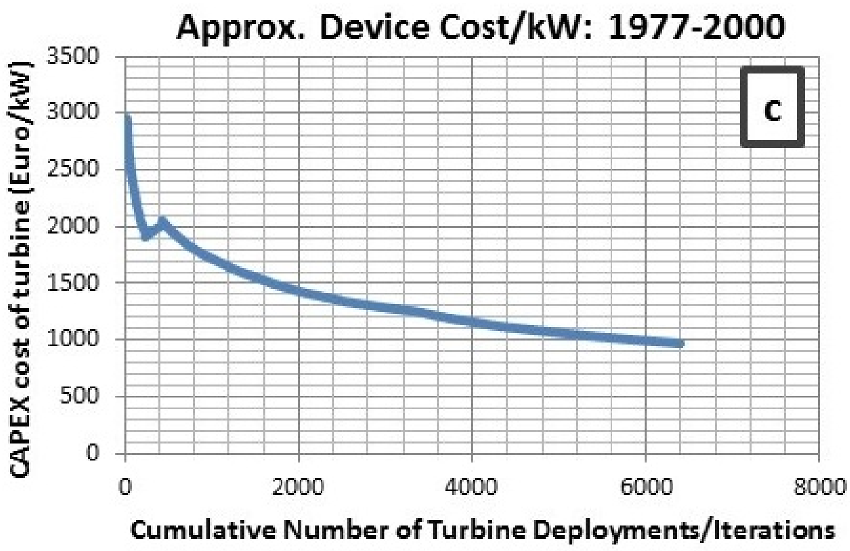

Figure 6.4: Wind turbine costs (price adjusted for inflation to 2015 prices), x-axis set as unit iteration number (c)

iteration in the early wind energy sector can be counted as economically sustainable, given the fact that the sector emerged from the formative phases to become an established commercial industry.

Wave and Tidal

With the wave and tidal energy sectors, there has not been sufficient deployment to generate adequate data for analysis. Recent analysis carried out within the SI Ocean project suggests a likely CAPEX for ocean energy devices of 4,300-9,000 €/kW (SI Ocean, 2013). However, these costs do not reflect the cost of deploying and testing a pre-commercial demonstration unit, and are estimates of the costs at the deployment of an early array.

The SI Ocean project assumes a cost breakdown whereby 45% of the total project costs can be attributed to the turbine (including PTO, control systems, and foundation). The first pre-commercial MW-scale tidal energy array in Scotland will cost over £51 million (approximately €61 million). The first stage of deployment will consist of four turbines. Using the SI Ocean project cost breakdown, this represents a cost of approximately €6.9 million per device (or 4,600 €/kW based on a 1.5MW machine).

While, in terms of cost/kW, CAPEX costs for the early array projects may not seem to be vastly different to the early wind energy costs, the total CAPEX costs per device in the early wave and

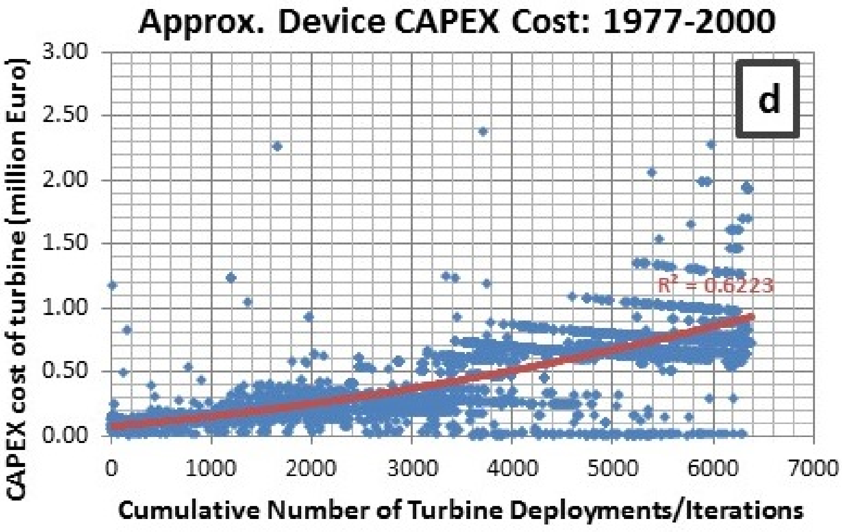

Figure 6.5: Wind turbine costs (price adjusted for inflation to 2015 prices), approximated average total device CAPEX cost with respect to unit iteration number (d)

tidal array projects represent almost two orders of magnitude in difference from the early wind turbine device costs. Strong investment from the private sector does not exist at this stage.

Market pull support mechanisms were introduced prior to the wave and tidal energy sector having achieved successful deployment and testing of pre-commercial demonstration technology. In addition, demonstrable cost reduction has yet to be achieved in the wave and tidal energy sector – subsequent build out of arrays is yet to materialise, but any cost reduction efforts need deployment in order to demonstrate successful progress.

Discussion on CAPEX Cost

There are two sides to the CAPEX discussion. Firstly, the CAPEX cost in terms of cost per kW; secondly, the total unit CAPEX cost. Wind energy technology in the late 1970s and early 1980s experienced high CAPEX cost/kW, but a reducing cost trend – over time and a significant number of deployments – resulted in competitive cost/kW by the late 1980s. By the time of the transition to a demand-pull dominated support mechanism, the CAPEX cost/kW was in the order of 1,400 €/kW.

Wind turbine technology, despite the high cost/kW, offered a relatively modest total CAPEX cost for early device iterations, due to the lower capacity of early devices. With average unit costs in the order of €100,000 during the early stages of industry development, many unit deployments were possible, as this CAPEX cost was within the reach of community groups and local investors.

A drive to reduce cost/kW in the wave and tidal energy sector has taken place through rapid unit level up-scaling. Wave and tidal energy technologies, due to the large unit cost of MW-scale devices, require a total CAPEX cost, per unit, almost two orders of magnitude greater than the early wind energy sector.

Wind energy was embraced by farmers and local community cooperatives; wave and tidal energy has not been embraced by utility companies and has failed to retain the investment of certain OEMs, and is beyond the reach of individuals or community groups under the current development focus.

The market mechanism within the UK has stimulated an accelerated rush to large-scale technology that can produce commercial scale quantities of power. The current mismatch between market expectations and the performance and deliverability of the technology is evident, and as a result, many established players within the wave and tidal energy sectors are withdrawing their interest in pursuing technology development at this stage. The requirement for deployment, through which cost reduction effects manifest, is currently a venture that few can afford.

The optimum wave and tidal stream energy technologies do not yet exist, and there is a continued need for technology push mechanisms to advance the core research and development process, before demand pull mechanisms will allow sufficient leverage to oversee the fruition of a mature market.

6.4.2 Metric 2 – Research and Testing

Research and testing forms a crucial part of the formative phase of technology development, as it offers a mode of assessing technological uncertainty across a range of competing designs, when appropriately carried out. Only through appropriate research and testing can a dominant design emerge as truly qualified to enter a new market. The geographic distribution of research and testing facilities, together with the appropriate capture and curation of knowledge, form the basis of this metric. A summary timeline for research and testing milestones relative to the shift between technology-push and demand-pull support mechanisms, for both wind and marine energy sectors, is presented in Figure 6.6.

Wind

Denmark had a scientific research base in the form of Risø National Laboratory, which pro-

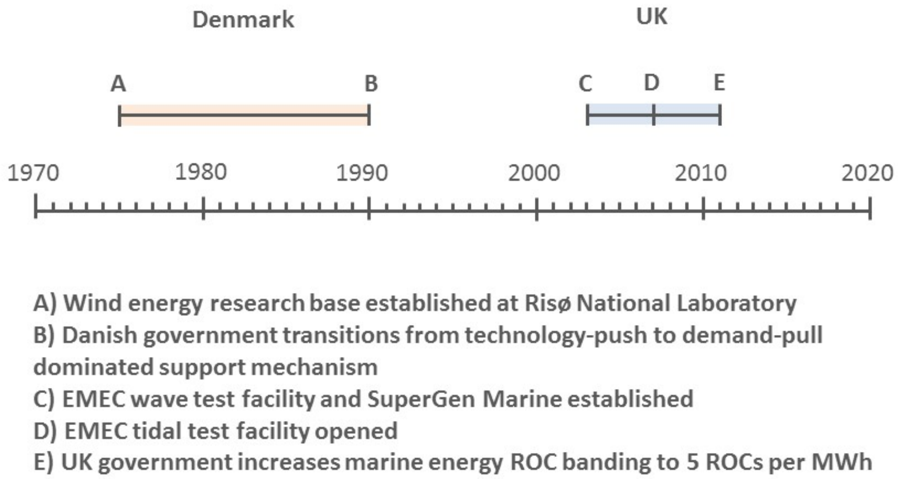

Figure 6.6: Timeline comparing the Danish wind and UK wave and tidal energy sectors in relation to Research and Testing before the transition to demand-pull support mechanism.

vided centralised research and test facilities for wind turbine R&D during the formative phase of wind turbine technology development. A strong culture of collaboration existed between industrial companies, academic research institutes, and government (Valentine, 2015). Risø was established in 1956, with its original focus in research related to electricity production from nuclear energy (Nielsen *et al.*, 1998). Wind measurements took place at the site, primarily to create a database of results that could inform likely propagation of radioactive particles in the event of nuclear incidents. However over time Risø's focus shifted away from nuclear power to renewable energy, in part due to the public opposition to nuclear power, and the country's need to strengthen its economy and broaden its energy portfolio (Nielsen *et al.*, 1998).

Risø's work on wind turbines was initiated in 1975, and in 1978 the National Station for Small Windmills was established. From 1986 onwards, Risø's official purpose was to carry out scientific and technological research centred on energy, in particular renewable energy (Nielsen *et al.*, 1998). Supported by a growing interest in alternative energy sources and government financial support, Risø began collaborating with manufacturers and developers in the wind turbine industry in the late 1970s. Risø National Laboratory was considered as a collective R&D department for Danish wind turbine manufacturers like Vestas, Bonus (formerly Danregn Vindkraft) and Nordtank, who were able to rely on Risø to help with technical issues and testing problems (Garrad, 2012).

Wave and Tidal

The UK has a range of world-leading testing facilities to support technologies through different stages of development (RenewableUK, 2013). This includes a number of small, medium and large-scale test facilities in laboratory and open water environments, as well as a variety of academic research groups specialising in wave and tidal energy (Mueller *et al.*, 2010). These research groups work both individually and collectively through partnerships in collaborative projects.

Due to the specialist nature of scientific research in the marine environment, the UK has developed distributed research clusters to focus on specialist core competencies. For early stage R&D (TRL 3-5), the UK marine energy sector has a number of small and medium-scale laboratory test facilities, and for open water demonstration and large-scale device testing there are test and demonstration centres such as the European Marine Energy Centre (EMEC) in Orkney, Wave Hub in Cornwall, and FaBTest in Falmouth Bay.

EMEC became the first major open water wave energy test facility in the world when it was established in 2003, however this facility offers a hands-off approach to engineering and technical certification, leaving this to individual technology developers. The SuperGen Marine Energy consortium in the UK was established in 2003, with the aim of achieving a step change in the development of generic marine energy technologies.

Research and Testing Discussion

The vast majority of Denmark's wind energy research and testing took place at Risø. This benefitted the sector by having the research community centralised and co-located (Nielsen *et al.*, 1998). In addition to improving the efficiency of research activity, the centralised research community within the Risø facility was pivotal in enabling learning by interacting – a process that resulted in practical technological solutions to address the engineering challenges emerging in the wind energy sector development (Valentine, 2015). Although marine energy research and testing is spread over the UK, each test centre and research group offers their own specialties to the sector. If they were to be pulled together then the sector could run the risk of diluting the specialties that each centre and group offers (Personal communition, 2014b). However, the disadvantage is that the distributed knowledge base in the UK marine energy sector is not used for the same certification processes and scientific support that the Danish wind energy sector was able to achieve with Risø. Research and collaboration takes place on a more ad-hoc basis between the marine energy industry and the scientific research base than was the case for the Danish wind energy sector.

Having established Risø National Laboratory as a scientific research base in 1975, the Danish wind energy research and test facility was accessible for 15 years prior to the Danish government transition to a demand-pull support mechanism. The UK on the other hand only had access to established research and test facilities for under a decade before the introduction of the demand-pull support mechanism in 2011. Research Consortia such as SuperGen, and the EMEC wave energy test facilities were established in 2003, resulting in a period of approximately 8 years in which stakeholders in wave energy had access to these resources. The EMEC tidal test facility was officially opened in 2007, resulting in a period of 4 years prior to demand-pull support mechanism introduction. The established UK marine energy sector expertise (in the form of world-class research and test facilities) existed for a little over half of the time that the Danish wind energy sector had access to Risø, and the approach to testing at EMEC is significantly different to the hands-on approach of the Risø facility. The wind energy sector made full use of this research facility before the transition to the demand-pull focused support mechanism, however wave and tidal energy is still significantly less mature in this respect. The importance of this additional accumulated experience cannot be underestimated when considering the development of each sector, given the level of development activity that took place within those formative years of the wind energy sector (Personal communition, 2014a; Garrad, 2012).

6.4.3 Metric 3 – Technology Development and Diffusion

Technology development has been characterised by the TRL scale, an approach formulated by NASA to determine the development status of a technology. The system uses a scale of 1-9, with 1 being the initial concept and 9 being the fully developed commercial application (SI Ocean, 2012). Modifications of the NASA TRL scale have been adopted by the renewable energy sector, which generally adopts a scale approach to TRL – full scale, at sea, pre-commercial testing is generally seen to represent TRL 7. Within this metric, an attempt is made to compare technological readiness with the level of diffusion into the energy market. A summary timeline for technology development and diffusion milestones relative to the shift between technology-push and demand-pull support mechanisms, for both wind and marine energy sectors, is presented in Figure 6.7.

Wind

Denmark's bottom-up approach to wind turbine development resulted in small wind turbines

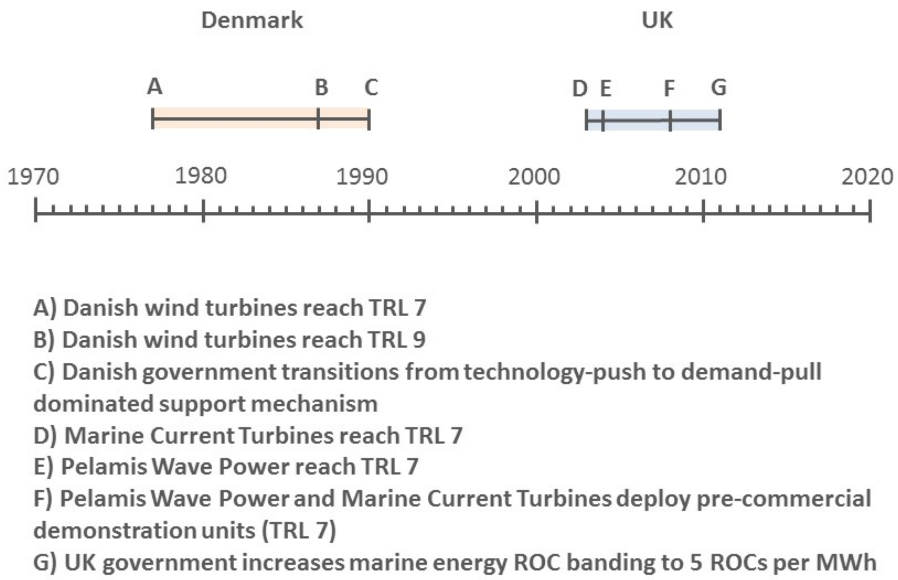

Figure 6.7: Timeline comparing the Danish wind and UK wave and tidal energy sectors in relation to Technology Development and Diffusion before the transition to demand-pull support mechanism.

dominating the early industry in the late 1970s. After successful small-scale deployment and operation, wind turbines with increased rotor diameter and increased capacity became available. It is difficult to identify specific points at which the Danish wind energy sector progressed along the TRL scale without subjectivity, because the size and capacity of wind turbines has been increasing ever since the 1970s, yet have been sold commercially throughout that time. Figure 6.8 shows the most common size ranges of wind turbines installed between 1977 and 1990.

In order to assess TRL, the assumption was made that to justify progression through the TRL pathway certain requirements had to be met, as outlined in Table 6.3.

Analysis of the Danish wind turbine register indicates that the sector progressed to TRL 8 (as defined in Table 6.3) in 1982. In 1983 over 50 turbines were again deployed within the 50-80kW range and an array of turbines was installed on the island of Fanø, suggesting increased levels commercial attractiveness associated with wind turbines. Before this point Denmark had already achieved a milestone of over 400 registered wind turbines installed and connected to the electricity grid. The vast majority of these turbines ranged between 15kW and 95kW in size, and all had been installed individually (and not as part of an array). Table 6.3 also indicates that Danish wind turbines had almost certainly reached TRL 9 by 1987, by which time over

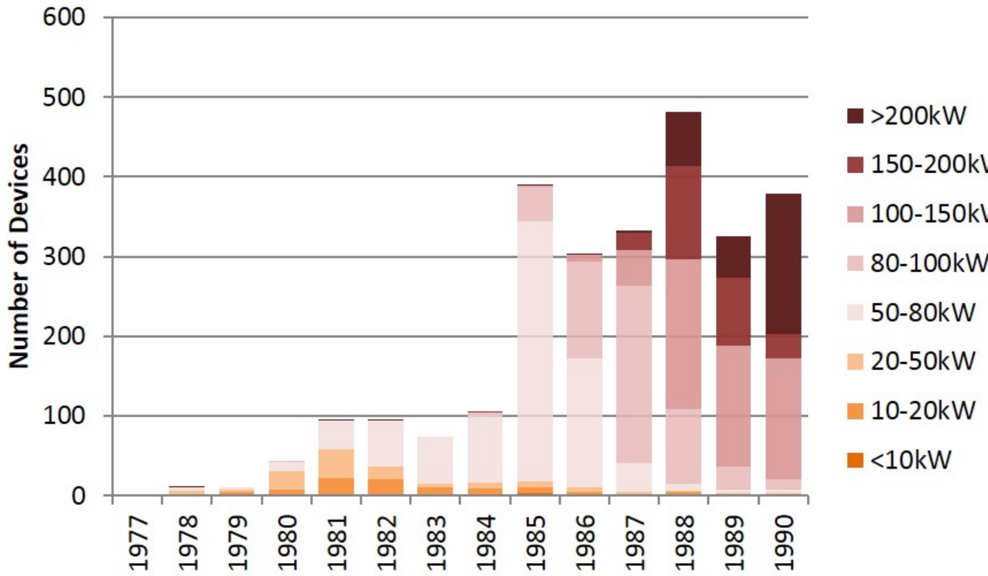

Figure 6.8: Bar chart: registered turbines commissioned in Denmark from 1978-90 and the associated ranges of capacity (Source data: (Energi Styrelsen, 2014)).

100 wind turbines of capacity greater than 50kW had been commissioned per year, for three successive years. It can therefore be said with reasonable certainty over a ten year period of development, the Danish wind energy sector developed wind turbine technology from TRL 7 to TRL 9.

Wave and Tidal

Proposed TRLs of wave and tidal energy converters in the UK marine energy sector are well documented in existing marine energy literature, although the exact definition of each TRL stage varies slightly between authors. Of all wave and tidal energy devices currently deployed in the UK, none are considered to be at TRL 9 (SI Ocean, 2012). Marine Current turbines deployed a 300kW horizontal axis turbine near the cost of Devon in 2003. Pelamis Wave Power deployed the first full-scale 750kW P1 device at the EMEC test facility in 2004. These deployments represent the demonstration of full-system prototypes, considered to be TRL 7. Despite the accumulated testing hours of a number of wave energy converters, industry experts rank the most advanced wave energy converters at TRL 7 (SI Ocean, 2012). In the tidal energy sector, two devices have accumulated significant GWh generation to the electrical grid: MCT (a Siemens business) SeaGen and the Andritz Hydro Hammerfest HS300. These technologies have been grid-connected for a number of years, but the sector as a whole has very few commercially available wave and tidal devices (SI Ocean, 2012). A number of device

Technology Readiness Level (TRL)	Description	Associated Timeline
TRL 7	Early full system prototypes successfully installed and demonstrated, <50 units of a particular scale installed in one year.	1977-1981
TRL 8	Technology considered to be completed and qualified - here considered to be the point in time when array deployment has taken place and >50 units of a particular scale installed in one year, suggesting increased confidence in system performance and improved economic performance of technology.	1982-1986
TRL 9	Technology considered to be fully proven and economically successful – here considered to be the point in time when >100 units of any technology scale have been installed for three or more consecutive years, suggesting product optimisation and development has made significant advancement and is now commercially attractive.	1987-present day

Table 6.3: TRL Level Advancement and Justification based on wind turbine master register analysis (Source data: Energi Styrelsen (2014)).

developers have deployed single-unit demonstration wave and tidal devices, but few have progressed past this stage of single-unit demonstration deployment.

Technology Development and Diffusion Discussion

The bottom-up approach used by Denmark allowed small and relatively inexpensive wind turbines (11-22kW) to be sold early on in wind turbine development. When the UK transitioned to a demand-pull based support mechanism, most wave and tidal devices being developed were in the region of 1MW, meaning that individual units are much more expensive to manufacture and deploy in comparison to Danish wind turbines at a similar point in their development trajectory.

By starting with small-scale technology, the Danish wind energy sector was able to rapidly iterate following a build-measure-learn cycle (with feedback loops allowing learning from previous unit iterations and deployments to filter in to subsequent designs). Starting with two turbine deployments in 1977, the Danish wind energy sector reached TRL 9 by 1987, by which time almost 1,500 turbines had been installed (Energi Styrelsen, 2014). This suggests that the Danish wind industry had a fully developed and mature technology, with significant historic evidence to support reliable unit operation, ready for the market for 3 years before Denmark transitioned to a demand-pull orientated support mechanism in 1990.

Wind energy development in Denmark offered a minimum viable product – a technology that, while not perfectly optimised, consisted of something that the market was willing to pay for. In this case, an environmentally sustainable source of power generation, and an alternative to nuclear power, which the general public were highly motivated for and favourably inclined towards (Karnœ, 1990). While national level research investigated heavy-duty, large-scale, MW-class turbines, the market for small wind turbines that were accessible to purchase and straightforward to maintain (or repair) flourished in comparison to the top-down science based approach adopted by the USA, UK, Germany and also, to an extent, Denmark (Karnœ, 1990).

The UK marine energy sector did not have any wave and tidal devices rated at TRL 9 when the UK government transitioned to a demand-pull orientated support mechanism (and still no technology at TRL 9 exists within either sector, three years after a transition to demand-pull based support mechanisms). Until the UK marine energy sector has a proven track record of multiple iterations of reliable device deployment and long term operation, the sector is unlikely to be ready to grow solely under the support of a demand-pull mechanism. Solo device testing does not allow for the same level of learning that can be achieved from multiple unit deployments, and the build-measure-learn feedback loop for marine energy prototypes is, in most cases, agonisingly long between subsequent unit deployments.

6.4.4 Metric 4 – Design Consensus

Emergence of dominant designs and front-running technology, together with attrition of non-optimal solutions, is expected as technological maturity is approached. Significant design diversity is reflective of early pioneering development, and of limited understanding of the optimal solution – as the optimal solution is unlikely to have been found. The investment requirements for bringing a technology to market mean that the sector cannot support the emergence of all technologies within the formative stage, and front-running technologies generally emerge once successful testing and demonstration has revealed solutions that are optimised in their performance. A summary timeline for design consensus milestones relative to the shift between technology-push and demand-pull support mechanisms, for both wind and marine energy sectors, is presented in Figure 6.9.

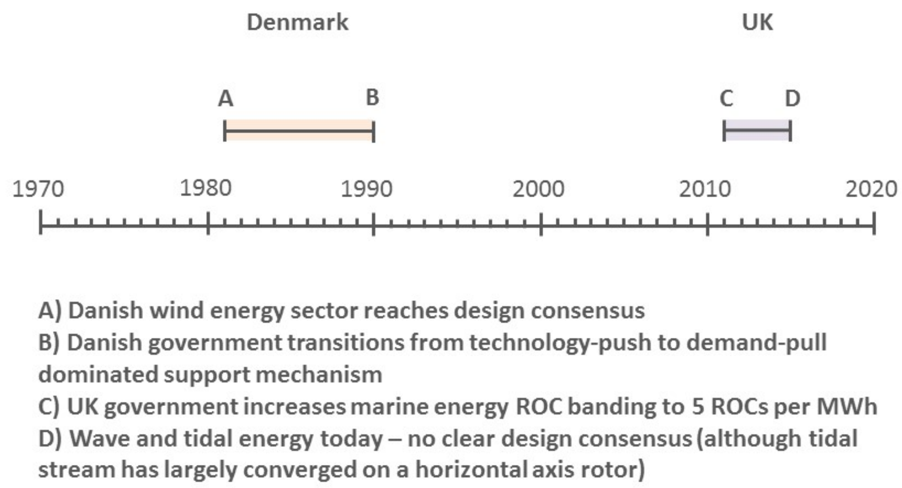

Figure 6.9: Timeline comparing the Danish wind and UK wave and tidal energy sectors in relation to Design Consensus before the transition to demand-pull support mechanism

Wind

In 1956, construction began on the Gedser Mill Wind Turbine (Figure 6.10 – left) designed by Johannes Juhl, which was operated successfully from 1959 until 1967 when declining fossil fuel prices made wind energy uncompetitive (Meyer, 2007; Vestergaard *et al.*, 2004). The Gedser turbine was the forerunner for the classic three-blade Danish design that is used today. The 200kW turbine had a rotor diameter of 24m, used a stall-regulation to limit the rotor torque, and utilised an induction generator, electromechanical yaw system and centrifugally activated blade-tip air brakes. One of the first Danish wind turbine pioneers, Christian Riisager, assembled a 22kW turbine based on a scaled down version of the Gedser turbine design, constructed using off-the-shelf-components in 1976 (Heymann, 1998). His 22kW wind turbine (see Figure 6.10 – right) marked the beginning of the successful bottom-up approach used by the Danish wind energy sector.

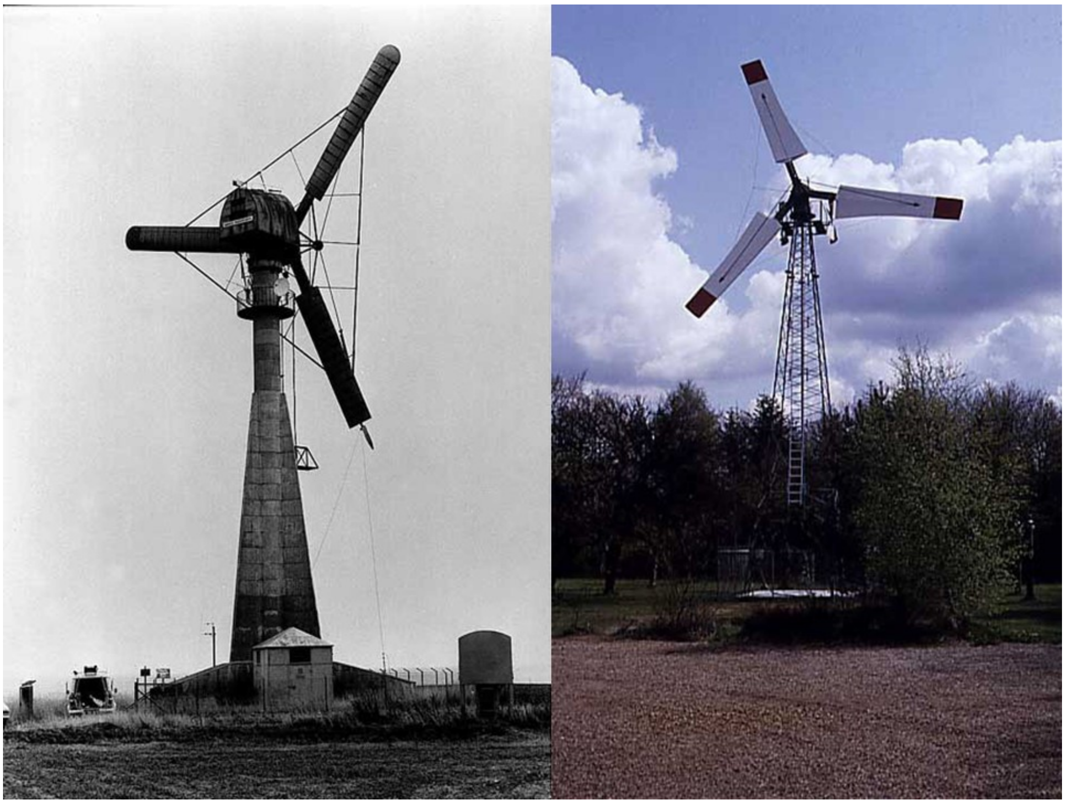

Figure 6.10: The Gedser turbine (left) and Riisager turbine (Right). Note the similarities in the turbine design. (Image Copyright Energimuseet, Bjerringbro, Denmark (Energimuseet, 2015))

The three-bladed horizontal axis wind turbine (HAWT) design is commonly known as the "Danish Concept" (Neij *et al.*, 2003). A combination of design principles from Juul, amalgamated with aerodynamic blades established from research conducted by Ulrich Hütter in Germany resulted in the pioneering wind turbine design that is prevalent to this day.

From 1981 onwards the vast majority of the Danish wind turbine industry developed its technology within a certain framework (Neij *et al.*, 2003):

- Horizontal axis;
- Upwind;
- Stall-regulated;
- Three-bladed;
- Grid-connected;

This design convergence ensured that the Danish wind industry reached consensus on optimal design at least 9 years before the transition to a demand-pull mechanism in 1990. The Danish concept continued to evolve incrementally throughout the 1980s and 1990s, but after the convergence in design, iteration was largely incremental in nature.

Wave and Tidal

The UK wave and tidal energy sectors are in contrasting positions with wind energy in regards to design consensus. In the tidal energy sector, although there are still other tidal device types under development, the industry has somewhat converged onto horizontal axis tidal turbines. A potential reason for this quasi-convergence to horizontal axis turbines is that these machines are already well understood in the wind industry; therefore technology transfer into an alternative fluid medium is seen as a credible application of technology transfer. However, design diversity still shows discrepancies in the number of rotors, the rotor diameter, and the foundation or mooring solutions employed within the framework of the horizontal axis turbine designs.

The wave energy sector on the other hand is more fragmented, with at least 6 different device types identified on the EMEC project website (Pressure Differential, Oscillating Water Column, Rotating Mass, Point Absorber, Oscillating Wave Surge Converter and Attenuator), and example technology in each category is still under development (SI Ocean, 2012). There is uncertainty as to which technology is most likely to succeed as the industry front-runner.

Design Consensus Discussion

Design consensus enhances aspects of industry development in that it allows the benefits of economies of scale to be reached at earlier stages of deployment; whereas a lack of design consensus restricts the pace of learning and development (Jeffrey *et al.*, 2013). Until design consensus has been reached, it is likely that there will be uncertainty among technology developers and manufacturers as to optimal allocation of R&D resources. The same argument could be made for government funding, in that without design consensus a government must spread investment as effectively and fairly as possible while trying to avoid ‘picking winners’ – potentially leading to the available funding being spread too thinly over a large number of technologies.

The UK wave and tidal energy sectors can be considered to still be in a state of design diversity, despite the transition to a demand-pull mechanism in 2011. Subsequent attrition of technology has taken place within both the UK wave and tidal energy sectors (OffshoreWIND.biz, 2014; BBC, 2014; Kennedy, 2014). Specific funding frameworks are only now beginning to open up significant opportunity to realise elements of design consensus, such as within the area of wave energy PTO, through collaborative research and development projects (Wave Energy Scotland, 2015b).

Until design consensus has been reached, the transition to a demand-pull dominated support mechanism is premature. Current experience suggests that private sector investment has insufficient confidence in the sector to maintain significant involvement. Confidence and certainty in design and performance is necessary in order to establish wider investor confidence in a given technology. Further iteration and technology development is needed in order to ascertain the optimised technology solutions that can become market ready – and thus bring the ocean energy sector into a position to capitalise on demand-pull support mechanisms.

6.4.5 Metric 5 – Certification

The certification metric represents the assessment, by an authorised and approved certification body, of how well a technology meets the demands and requirements placed upon it, and confirmation that the technology meets intended design objectives to a high standard. The certification process must be officially recognised if it is to be credible in its influence on technology development. A summary timeline for certification milestones relative to the shift between technology-push and demand-pull support mechanisms, for both wind and marine energy sectors, is presented in Figure 6.11.

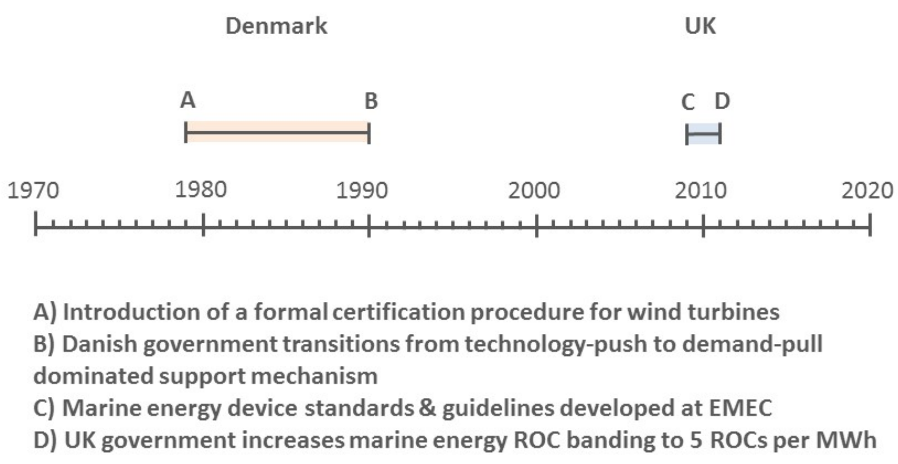

Figure 6.11: Timeline comparing the Danish wind and UK wave and tidal energy sectors in relation to Certification before the transition to demand-pull support mechanism.

Wind

In a similar manner to the centralised research and testing facilities offered by Risø, quality control methods and certification procedures were also standardised and centralised in the early Danish wind energy sector. In 1979, approximately one year after the National Station for Small Windmills was established at Risø, a formal certification procedure was implemented for wind turbine design. The Danish government was instrumental in supporting this certification procedure by stipulating that in order to be eligible for the 30% capital grant subsidies for wind turbine installations, each wind turbine had to pass Risø's formal certification procedure (Meyer, 2007). The Risø certification procedure was essential in preventing sub-optimal technologies from being marketed both domestically and internationally, and ensured Danish wind turbines demonstrated and maintained a solid reputation for reliability (Meyer, 2007). This was a strong motivation behind Californian imports of Danish wind turbines during the wind power boom of the 1980s. Denmark was one of the first countries to promote aggressive quality certification and standardisation programs for wind turbines. In addition to this rigorous certification process, the Danish government also favoured the development of local manufacture (Lewis and Wiser, 2007).

Standards and formal certification are a significant step in the development of any technology. A fundamental way to promote the quality and credibility of a technology is through participation in a certification and testing programme that meets international standards (Lewis and Wiser, 2007). In the case of the wind energy sector, international standards for wind turbines (IEC 61400) were not formally published until 2001, well after Denmark introduced its main demand-pull mechanism. However the sector already had the benefit of a formal certification procedure, which had been in place since 1979 at Risø National Laboratory, 11 years before the government transitioned to demand-pull support mechanisms.

Wave and Tidal

The marine energy sector does not currently have international standards for marine energy devices. However, The European Marine Energy Centre (EMEC) developed a suite of 12 standards and guidelines for marine energy devices on behalf of the marine renewables industry in 2009 (EMEC, 2013a). These standards and guidelines propose measures for performance, device reliability and survivability, assessing wave and tidal site resources, design and manufacturing and also health and safety. The International Electrotechnical Commission are responsible for the development of a suite of internationally recognised standards, TC 114: Marine energy – "Wave, tidal and other water current converters" within the IEC 62600 framework (International Electrotechnical Commission, 2015). While certain work programmes within TC

114 have reached approval for publication, many of the specifications remain work in progress, with publication of standards forecast to take place between 2015 and 2017 (International Electrotechnical Commission, 2015).

Discussion on Certification

Although the UK marine energy sector has had access to EMEC guidelines since 2009, these are only guidelines and are not enforced in the same way that Denmark applied rigour to the certification of wind turbines. Furthermore, the certification process of wind turbines at Risø involved, to a much greater degree than exists within the marine energy sector, a level of transparency between technology developers, research organisations, and the certification bodies. This allowed knowledge to benefit the development of a sector, rather than just a single technology. It is vitally important that the marine energy sector has recognised international certification processes and standards in order to provide international credibility. Standards and certification processes help to build consumer confidence in an otherwise unfamiliar product, such as a wave or tidal energy converter. Until the UK marine energy sector adopts specific technical standards or employs a formal and enforced certification procedure, there is no mechanism for consistently ensuring that materials, sub-systems, systems and prototypes are fit for purpose as long-term assets within the power generation mix. Type Certification is often sought by wind energy technology developers in the latter stages of development, to prove to investors that manufacture has taken place to approved designs, and that the design is fit for purpose. There is also a need for those within the ocean energy sector to fully realise the value of transparency of data, and to embrace a similar enabling attitude to the approaches taken by Risø in the early stages of wind energy development.

6.4.6 Metric 6 – Experienced Developers

The number of experienced developers within a given sector can be an indicator of the maturity of technology, and the success of technology development within an industry. A summary timeline for experienced developer milestones relative to the shift between technology-push and demand-pull support mechanisms, for both wind and marine energy sectors, is presented in Figure 6.1.

Wind

The beginning of the wind energy sector in the 1970s coincided with the decline of the agriculture sector in Denmark and the 1973 oil crisis. As a result of shifting trends, certain agricultural and oil services companies such as Vestas, Bonus, Micon and Nordtank entered the wind energy market (Garrad, 2012; Smith, 2011). Over time, mergers and acquisitions resulted in an industry shakeout, consolidating technology within the market.

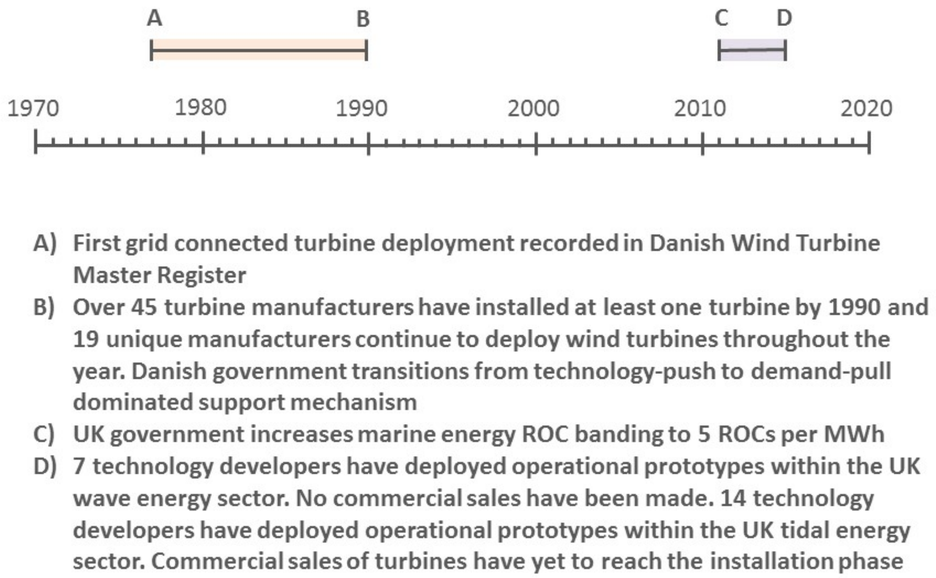

Figure 6.12: Timeline comparing the Danish wind and UK wave and tidal energy sectors in relation to Experienced Developers before the transition to demand-pull support mechanism.

An important factor that contributed to the growth of companies like Vestas, Nordtank and Bonus was their industry experience and access to capital, which was far greater than that of the start-up companies. The larger industrial firms benefited from the support of the pro-renewables Danish government, assistance from Risø National Laboratory, and a strong domestic market. Risø was a collective R&D base for wind turbine developers in Denmark and helped these developers grow organically within Denmark without the need for foreign investment (Garrad, 2012).

By 1990, 45 companies had deployed wind turbines – and five of those manufacturers had installed over 100 devices. Although Danish companies benefitted from a growing export market (such as California in the 1980s), the main source of industry growth was organic within Denmark. By the end of 1990 there were over 2,667 grid-connected wind turbines in Denmark, with 316 belonging to Bonus and 676 belonging to Vestas. A total of 19 wind turbine manufacturers deployed wind turbines in Denmark throughout 1990. The top wind turbine manufactures in order of number of devices deployed by the end of 1990 have been highlighted in Table 6.4.

Manufacturer	Number of Devices Deployed by end of 1990
Vestas	676
Bonus	316
Nordtank	300
Windmatic	163
Windcon	78
Wind World	69
Danwin	57
NEG Micon	55
Micon (pre-NEG)	42
Tellus	35

Table 6.4: List of top ten wind turbine manufacturers in Denmark at the end of 1990.

Studies on innovation in the wind energy sector have shown that the dominance of companies like Vestas, Bonus and Nordtank stemmed from first-mover advantage (Lewis and Wiser, 2007). This made it very difficult for foreign wind turbine developers to enter into the Danish market. By the end of 2004, 99% of all grid-connected wind turbines in Denmark were made by domestic companies. In comparison, domestic wind turbines accounted for 73% of the market in Spain, and 54% of the market in Germany. This highlights the dominance that Danish wind turbine developers had in their domestic market, and also in export (Lewis and Wiser, 2007).

Wave and Tidal

The wave and tidal energy sector is fragmented, with much design diversity. Over 250 wave energy technology developers and over 110 tidal energy device developers have been identified by EMEC. Many of these developers are at the prototype stage, and very few have achieved physical deployment of technology. In the UK there are many wave and tidal energy device developers trying to establish themselves as industry frontrunners. Over the last few years in particular there has been some major investment in the marine energy sector from large engineering firms, predominantly in the field of tidal energy. Some of these examples are listed below:

- Siemens acquired Marine Current Turbines (February 2012);
- Andritz Hydro acquired a majority share in Hammerfest Strom, forming Andritz Hydro Hammerfest (April 2012);
- Alstom acquired Tidal Generation Limited from Rolls Royce (January 2013);
- DCNS becomes a majority shareholder in OpenHydro (March 2013);
- Atlantis purchases Marine Current Turbines from Siemens (April 2015);

The large percentage of foreign investment in UK marine energy companies is in stark contrast to early organic growth of Danish wind energy companies. Despite the investments that have been made, many companies have struggled to attract further private sector investment. Furthermore, most of the companies active within wave and tidal energy are yet to deploy more than one device. As such, these ocean energy companies lack the maturity that comes with installing large numbers of devices – experience which the Danish wind energy sector had in abundance.

Discussion on experienced developers

While some marine energy device developers can be considered to have been active in the UK for almost a decade, these technology developers have not had the device deployment experience that Danish wind turbine manufacturers had achieved within a decade of technology development of the wind energy sector. Marine energy technologies, without a significant level of deployment, find themselves in a demand-pull dominated policy framework. However, demand-pull support mechanisms are premature for the stage of industry development, as they are not able to foster the correct level and intensity of technology development within a formative phase of technology development.

6.5 Policy Conclusion

Analysis of the policy landscape within wave and tidal stream energy enabled a comparison to be drawn between the current policy climate in the development of novel technology, and the historic policy support that enabled wind energy to successfully emerge from niche product into widespread diffusion.

Wind energy policies were not always well defined, and were not necessarily proactively implemented. A number of wind energy policies were reactive in nature, but Denmark showed significant flexibility in order to adapt the policy support to the developmental needs of the technology at the time. With regards to the specific metrics discussed herein, a number of conclusions can be drawn.

The initial CAPEX cost of wind turbines, although high in terms of cost-per-kilowatt, was modest in terms of cost per unit iteration. Use of small-scale technology in the order of tens of kW enabled affordable unit iteration. Increasing experience through manufacture and deployment of wind turbine technology resulted in significant learning and technology up-scaling. Decreasing cost/kW was experienced in tandem with increasing unit costs, as technology evolved towards larger capacity units. The ability to raise the necessary finance for larger technology models was based upon recognised confidence in the performance of earlier models. By the time a transition to demand-pull dominated support mechanisms took place in the wind energy sector, CAPEX costs had reduced to around 1,500 €/kW, with average unit cost of approximately €200,000. In the wave and tidal energy sector, a wide range of CAPEX costs exist – in part due to uncertainty of unit costs in the conceptual stage, and in part due to the diversity in design of different technology types. This CAPEX cost range is approximately 4,800–12,000 €/kW. While device costs are dependent on the scale of the unit in question, many developers are attempting development of MW-scale technology, resulting in unit costs that are several million Euro in magnitude. For formative stage technology development, this represents significant economic and technical risk for a product that is not guaranteed to perform as expected. Despite these significant deviations from known successful technology trajectories, ocean energy policies have transitioned to demand-pull dominated support mechanisms with MW-scale technology development in mind.

The central research and testing facility at Risø encouraged a strong growth in knowledge capital dedicated to wind energy resource and technology development. As well as offering in-house knowledge and expertise, Risø offered assistance in the proving and development of technology, and certification of components and devices, giving confidence to investors and stakeholders. This hands on support is very different to the academic research expertise and test centre facilities within the wave and tidal energy sectors, which have a distributed knowledge base spread across a large geographic area. Although collaborative work is visible, this is very different to the rigorous approach to certification adapted by Risø in the wind energy sector's development. A transition to demand-pull orientated support mechanisms came after a decade and a half of expertise had developed within the Risø framework. Wave and tidal energy has access to test facilities, but with a very different approach to that of Risø. The resource is far less understood, and the technology performance within this resource perhaps not optimised, yet still a transition to demand-pull orientated support mechanisms took place within a decade of development (but with very little deployment in comparison to wind energy).

Wind energy technology development utilised a number of technological iterations before settling upon a dominant design. Although there were customers for early wind turbines, the dominant design emerged after a formative phase of trial, error, adaptation and improvement. Diffusion of technology took place after a significant level of unit iteration had taken place. Large numbers of unit deployments at early TRL allowed confidence in technology to increase, allowing growth in technology unit-scale and the industry-scale diffusion that resulted. Demand-pull support mechanisms only became the dominant form of policy support for wind energy after over 2,600 unit deployments had taken place. Until this point, a number of technology-push and demand-pull support mechanisms were constructively utilised to encourage and sustain a domestic wind energy sector in Denmark.

Ocean energy technologies have transitioned towards demand-pull dominated policy support mechanisms prior to comprehensive formative development. Furthermore, there have been very few technology iterations, and design convergence has not been experienced. With such a diversity in design, wave and tidal energy incentive mechanisms are stimulating large scale output prior to devices having demonstrated consolidated reliability and optimised design, which is a flawed approach in comparison to that followed by the wind energy sector.

Chapter 7

Discussion of Findings and Conclusion

7.1 Chapter Introduction

This section will draw together specific findings from each of the three main analysis chapters 4, 5, and 6, in order to build a comprehensive evidence base that suggests the push for 'accelerated innovation' and rapid up-scaling and deployment of large scale technology within the wave and tidal energy sectors is not conducive to the economically sustainable development of each technology type, nor the emergence of a commercially viable technology through an appropriate formative phase of development. The main discussion points from each chapter, and their implications with regards to redefining an appropriate policy framework will be presented in turn.

7.2 Technological

7.2.1 Discussion

Technology optimisation, iteration, deployment and learning all feed in to the progression of technology from nascent stages of development to maturity. Optimisation requires iteration, regardless of the perceived state of knowledge at the outset of a sector's development. There are clear lessons from the wind energy sector that point to the dangers associated with immediate progression into deployment of the largest conceivable technology scale – not all existing knowledge can be directly transferred to a new sector, and bigger is not always better (Gipe, 1995).

Observation of historical trends suggests that there is great impact and value associated with iteration and the operation of multiple units at small scale. This allows for both learning by doing and a convergence in design around the most optimal solutions prior to expenditure on significantly more capital intensive products or projects as the unit capacity increases.

From the analysis of each technology using 5PL functions carried out in Chapter 4, it is clear to see the initial devices deployed consisted of units that were only a small fraction of the capacity of the upper asymptote value, T (0.0005%, 10%, 0.2% and 0.3% of T for steam turbines, gas turbines, wind turbines, and solar PV arrays respectively). At the point in which the establishment of significant unit-level up-scaling took place, unit capacities still represented only a portion of the asymptote value, T, or the current maximum unit capacity (13%, 21%, 6%, and 16% of T for steam turbines, gas turbines, wind turbines, and solar PV arrays respectively).

Within the analysis, devices deployed between the initial unit and the unit at x_i represent the formative phase of the technology. It can be seen that a rapid increase in unit-level up-scaling did not occur instantly in any of the historic cases investigated, but took a formative phase deployments. Within steam turbine technology, data suggests the formative phase consisted of 799 unit deployments. In the case of gas turbine technology, which had the advantage of developmental input from aviation and heavy industry not considered within this thesis, 759 unit deployments took place within an electrical power generation context prior to unit-level up-scaling becoming well established. Wind turbines, often considered analogous to the wave and tidal energy sectors due to the modularity of the units, required deployment of 3,636 units prior to the establishment of significant unit-level up-scaling. Solar PV arrays required the deployment of 459 arrays prior to the establishment of significant and continued up-scaling. The wind and solar PV industries did, however, demonstrate that it is possible for industry level up-scaling to take place prior to unit level up-scaling. However, the industry up-scaling was able to benefit from a well-developed product in which much evidence of reliable unit operation could be drawn from historic deployment experience.

The energy sector has evolved over the last century, and the innovation environment in which modern technology development is taking place has changed significantly from that of the historic energy sector. New tools and processes available to engineers allow simulation and testing of components and systems before they are even built, courtesy of advances in computational tools and simulation capabilities. Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), Rapid prototyping and 3-D printing are resources that were not available to engineers involved in early steam turbine development, or in early gas turbine design. These tools can help to reduce the cost of testing, and accelerate aspects of design. However, they are not a replacement for physical testing, which must also be carried out to validate any models or simulations that are run.

Innovation does not occur through an independent one-off event; rather it is the result of multiple generations of product iteration (and along the way, some technology failures – at a sub-component or subsystem level, even if not full system – should be expected as inevitable) through which knowledge is pooled to create a framework for a successful new product or company. History has proven that these lessons are best learned at small scale, yet the majority of marine renewable energy technology developers are attempting to bypass this formative phase, instead choosing to focus on rapid up-scaling with an expectation of imminent commercialisation, without yet having a commercially competitive product to offer.

Attempting to iterate at MW scale is expensive, and the lessons that could more cost-effectively be learned at an earlier stage of development through deployment of multiple smaller-scale device units are being overlooked. This theory has also been raised before in the outlining of Technology Performance Levels (TPL) as an indicator for the economic performance of an ocean energy converter (Weber, 2012), however the wave and tidal energy sector development has largely failed to respond to this concern. Issues such as marine growth, bio fouling, environmental impacts, the effect of turbulence on device operation, device-device interaction, device noise characteristics, data collection and sensor operation, device performance in a wide range of sea conditions, and installation and O&M techniques all contain unknown parameters that create uncertainty in development of the sector from a technological perspective. These fundamental lessons should be learned within a formative stage of technology development, and where these lessons have not yet been learned, a push for commercialisation is premature.

Although success stories are needed within the wave and tidal energy sector to elicit continued sector support, it is not uncommon for early products or prototypes to go through a 'burn-in' phase, whereby early failures or weak links in the system can be exposed and removed (Block and Savits, 1997). The first product is rarely perfect; every good product is born out of lessons learned. For development of this new sector to achieve credibility, there is a need to iterate and learn lessons at an accelerated rate compared to current achievement. These early lessons through learning by doing will help to establish improved technology for future technology iterations.

In the book 'To Engineer is Human: The Role of Failure in Successful Design', the author states that "no one wants to learn by mistakes, but we cannot learn enough from successes to go beyond the state of the art" (Petroski, 1992). 'The Lean Startup' suggests that one of the greatest lessons of the scientific method is this: "If you cannot fail, you cannot learn" (Ries, 2011). At MW scale, failure and 'lessons learned' could spell bankruptcy for an ocean energy technology developer due to the cost of redeployment, or even the retrieval of a failed device. The cost of failure is severe, and accentuated when failures occur at large technology scales (Grubler *et al.*, 2014).

This research has outlined that there could be a route that would better achieve the desired results of reliable technology, sustainable development, and a more affordable investment, than through continuation down the current deployment trajectory: iterating at small scale, using validation from testing to improve and optimise technology, learn lessons through deployment of technology prior to the progression on to more heavily capital intensive MW-scale deployments. This research is not suggesting that quantity over quality is needed; however a quantity of quality is necessary to demonstrate viability at a commercial and industrial scale. However, a word of caution must be mentioned – devices that cannot be subsequently scaled up should be avoided, as future up-scaling should be targeted once a formative phase of technology development has taken place.

7.2.2 Conclusions

The development pathway successfully followed by mature energy technologies demonstrates progression through a formative phase, before up-scaling and growth phases, over a number of unit iterations. Wave and tidal energy technologies are attempting to bypass the formative phase of development, omitting an essential step in proving availability, affordability, survivability and performance of technology. This attempt by ocean energy technology to bypass directly into a commercial environment should not be considered as an appropriate trajectory, signalling a flawed research, development, and innovation environment. This section has clearly demonstrated that the focus of technology development within the formative phase of the wave and tidal energy sector would perhaps be better directed through meeting the requirement of affordable unit iteration, and not on seeking rapid technology up-scale. Multiple unit deployments, often at smaller scale, are effective in stimulating innovation through iteration, allowing a more granular and modular approach to technology development across many units.

7.3 Economic

7.3.1 Discussion

Wave and tidal energy technologies offer much potential if economic extraction of the resource can take place, however current concepts represent technologies that are attempting to break in to a competitive marketplace, but without a cost-competitive product. The deployment of novel wave and tidal energy converters is reliant on government incentive mechanisms in order to provide an attractive business case in which a project can be considered bankable. The global financial crisis has caused contraction in R&D investments globally, and investors have been more cautious when considering the required returns in order to make an investment attractive (European Commission, 2015). Modest levels of funding directed towards wave and tidal stream technology development has been available, and many technologies have utilised this funding, together with leveraged investment from the private sector, to develop large scale technology prototypes. Although several devices have reached the milestone of having a 'full-scale pre-commercial demonstrator', very few technologies have progressed from single device demonstration.

Technology cost reduction is primarily a function of deployment, not primarily a function of time. Without fabrication and deployment, effective learning by doing cannot take place – and costs will not reduce. Without cost reduction, the likelihood of substantial deployment is slim. Starting from a position of analysing other energy technologies – with particular emphasis on the experienced learning rates and the level of deployment before sustained cost reduction was achieved, it can be seen that projections made in existing industry reports by the wave and tidal energy sector are, in comparison, extremely optimistic – particularly with regards to the capacity at which shakeout and sustained cost reduction occurs.

By constructing a range of learning curves based upon input parameter ranges, it has been possible to ascertain a large number of plausible cost trajectories in which wave and tidal energy technologies could follow, providing guidance on the range of total investment requirements, and the cost over and above alternative cost-competitive energy technologies (the learning investment).

The database created from this research contained the results for an extensive 14,200 scenario possibilities. The initial learning investment sensitivity analysis undertaken within this thesis has demonstrated that the learning investment cost associated with ocean energy deployment is subject to significant uncertainty – minor perturbations in the input parameters can have a dramatic effect in the overall learning investment requirements. The affordability of the current research, development and innovation environment is in question, as each iteration of deployment using large-scale technology results in significant capital expenditure. In order to reach cost competitiveness with offshore wind, optimistic deployment trajectories will need to be met – significantly improving on statistics that were achieved within the offshore wind sector in terms of both LR and CSCR.

Investigation of learning investment requirements for continuation along a MW-scale technology trajectory concluded that mean and median values for the learning investment up to 10,000 unit deployments was £11.52 billion and £8.35 billion. In contrast, the learning investment requirements for pursuit of a kW-scale technology trajectory up to 10,000 units was £2.58 billion and £2.4 billion respectively. Large and small scale learning investment mean and median values are compared in Figure 7.1.

Considering a formative phase of development involving 1,000 large-scale unit deployments, the learning investment mean and median values become £2.76 billion and £2.7 billion. If the 1,000 unit deployment was to consist of small-scale technology, the learning investment mean and median values become £0.5 billion, as shown in Figure 7.2.

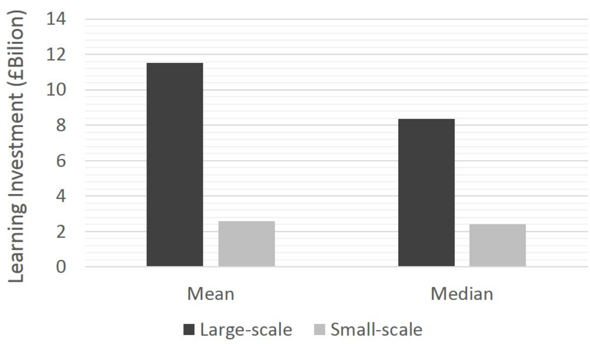

Figure 7.1: 10,000 Unit Deployment: Learning Investment Summary for Large-scale and Small-scale Technology

The probabilistic nature of the simulations allowed the 10th, 50th, and 90th percentile to be defined for the modelled simulations, as shown in Table 7.1. The results clearly indicate that there is a high probability that 10,000 unit deployments at small-scale could be carried out within a similar learning investment to 1,000 large-scale units. This is an important finding of the research, as it demonstrates that although CAPEX cost/kW may be greater for small-scale devices at the outset of deployment, similar deployed capacities can be reached to that of large

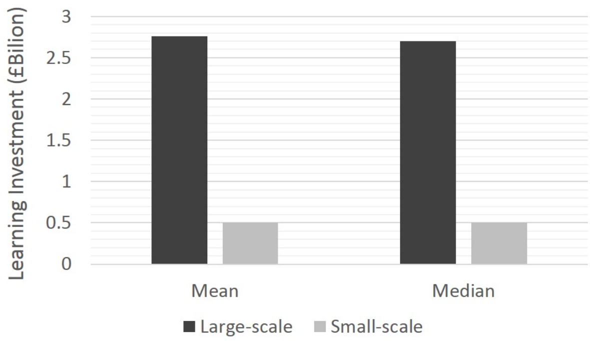

Figure 7.2: 1,000 Unit Deployment: Learning Investment Summary for Large-scale and Small-scale Technology

scale depoyment, albeit with greater levels of deployment experience and unit iteration – there is a greater likelihood that a more optimised technology will have been developed.

Technology Scenario	P_{10} (£bn)	P_{50} (£bn)	P_{90} (£bn)
Large-scale	1.5	8.35	26.1
Large-scale Formative	1.3	2.7	4.3
Small-scale	0.6	2.4	4.8
Small-scale Formative	0.29	0.5	0.73

Table 7.1: Percentiles and the Learning Investment.

If we consider deployment out to 10,000 units, there is a 50% probability that the learning investment for wave and for tidal stream could exceed £8.35 billion if MW-scale units are used. By following a kW-scale technology trajectory, there is a 50% probability that the learning investment could be less than £2.4 billion.

If we consider a 1,000 unit formative phase, there is a 50% probability that the learning investment for wave and for tidal stream could exceed £2.7 billion under a MW-scale deployment trajectory. There is a 50% probability that the learning investment could be less than £500 million if kW-scale technology is used.

While, undoubtedly, small-scale technology only offers a portion of the overall installed capacity that would be offered for large-scale technology on a unit by unit basis, a formative phase by its very nature requires experimentation and iteration in order to optimise a technology. The first unit is extremely unlikely to be flawless. Up-scaling and future industry growth would be expected of both wave and tidal stream energy technologies, but only after successful emergence from a formative phase of development.

A shift in focus to more affordable technology iteration and unit cost would allow CAPEX cost reductions (in terms of £/kW) to take place within a significantly reduced learning investment compared to a MW-scale technology trajectory. The challenge for ocean energy technological innovation is to deliver a reduced cost of energy in the short-term and to sustain continued long-term sustained cost reduction over several magnitudes of deployment – which becomes increasingly harder to achieve with increasing levels of deployment (Barreto, 2001). If, like wind, the sector needs to achieve substantial deployment in order to facilitate learning and cost reduction, then there is a real risk that there will not be sufficient funding or appetite to invest in the available technologies at this stage in the sector development.

While the current aspirations of the wave and tidal energy sector may be correct in terms of the eventual commercial viability of utility class ocean energy technology using MW-scale devices, the route to achieving the goal of commercialisation requires a step-change from the current trajectory. This research suggests that increased efforts into the development and deployment of small scale devices would allow ocean energy technologies to progress through the formative phases of technology development at a significantly reduced cost compared to MW scale technology. A small-scale approach to development would present a more economically sustainable formative phase, whereas continuation down the current trajectory involves substantial economic risk. Perhaps it is this step-change in perspective that will be necessary in order to enable the ocean energy sector to reach true maturity through evolution: a technology cost that could be considered affordable and achievable within an accelerated time frame; technology that is capable of providing a reliable and robust contribution to the global energy mix.

7.3.2 Conclusions

If an affordable formative phase and manageable economic risk are criteria that policymakers and investors wish to enable, the uncertainties associated with large-scale technology deployment do not make for comfortable viewing. This research has demonstrated that a research, development and innovation environment focusing on research, development and optimisation of small scale technology prior to widespread commercial roll out and industry growth could significantly reduce the economic uncertainty and overall cost associated with achieving the industry goal of commercially available technology. It appears, under the assumptions that were inherent to this model, that economically sustainable development of wave and tidal energy sectors has a higher probability of success if small-scale technology is used within the formative phase of development.

Regardless of the pathway chosen for future ocean energy research, development and innovation, an international collaborative approach will be necessary – the costs associated with ocean energy technology development, deployment and commercialisation are likely to be significantly more than one country alone can support. A trans-national collaborative effort must take precedence over a winner takes all attitude if successful commercialisation of ocean energy technologies is to take place.

This study has focused on CAPEX only (omitting OPEX costs – which are deeply uncertain at this stage in development, regardless of technology scale), and the conclusions may be limited to the formative phase of development only, rather than being applicable to the wider long-term commercialisation and build out of the ocean energy sector. Ultimately, ocean energy technologies will require to reach MW-scale units in order to be of interest for utility scale projects, and this research recognises that up-scaling will be required at an appropriate stage in technology development in order to achieve this aim. However, the focus at present should be on produced energy rather than on maximising installed capacity, and the approach of ‘starting large’ creates significantly greater technical and economic uncertainty compared to a smaller-scale technology approach to formative phase development and deployment.

7.4 Policy

7.4.1 Discussion

Political will has the opportunity to make or break an industry. Strong support directed appropriately can allow the formation of supply chain and markets securing successful technology development and diffusion; however, inappropriately directed policy can stimulate the wrong type of development, pick sub-optimal ‘winners’, or fail to allow dominant technology to emerge. A delicate balance of both technology-push and demand-pull support mechanisms is necessary, particularly within the formative stages of technology development where public sector investment may be limited – as is the case with wave and tidal stream energy. While specific support mechanisms are rarely kept constant throughout the development cycle of technology, apposite policy support frameworks are essential in order to enable a wider vision to be realised.

From a policy perspective, one of the drivers for ocean energy investment is long term commitment from government. One way in which this commitment could be manifest is through targets that require the installation of ocean energy – historically demonstrated in the ocean energy sector by a commitment to reach a target deployed capacity in MW or GW within a specific time-frame – and a favourable Feed-in-Tariff (FiT) mechanism to provide consistent revenue throughout the life of the project. However, technological maturity has not yet come of age within the wave and tidal energy sectors.

Wind energy policies in Denmark were effective and flexible in that although not all policies adopted were successful, the policy framework was not so rigid as to prevent deviation towards policies that were more apt for the needs of the technology under development at the time. There was recognition of the need to achieve deployment and utilise niche markets, and the policy framework was adapted as necessary in order to allow this build out of technology. While policy support entailed a number of different mechanisms, a transition to a demand-pull dominated support mechanism did not take place within the wind energy sector until significant long term operation of technology had taken place – a large number of commercial turbines were in operation prior to this transition, and the technology was considered to be mature. Further and continued development is still taking place within the wind energy sector today, but the technology has long been established.

The transition towards demand-pull dominated policy support in the wave and tidal energy sectors came amid significant technological and economic uncertainty – which is still ongoing to this day. Significant design diversity is still in place. Very few, if any, operational prototypes exist in which continuous and sustained operation has taken place autonomously for prolonged periods of time. Based on the results of the metric analysis in Chapter 6, ocean energy technology is not yet mature. In comparison to the wind energy sector, which successfully emerged as an energy alternative to conventional fossil fuelled power generation, ocean energy lags in development maturity but a transition from technology-push to demand-pull incentive mechanisms has already been made. This has not proven to be a successful route to commercial operation, and a change in strategy is necessary in order to re-align the policies and support mechanisms with the true technological development needs of the sector if an economically sustainable and commercial industry to emerge.

Allowing technology development to be driven by market incentives alone is likely to lead to a slower commercialisation than is necessary. A ‘long term engineering view’ rather than a ‘short term financial view' must be adopted by investors in marine renewables if there is to be long term success in the industry (Garrad, 2012).

7.4.2 Conclusions

Policy makers have been creating incentives for technology development to enter into a phase of pre-commercial demonstration prior to technologies achieving physical technological readiness for such scale. Furthermore, once set in motion, programmes such as these become difficult to terminate even if they do not reach intended technical or cost objectives – they become 'political prizes' because of their potential to be headline material (Weyant, 2011). The backers and investors behind such large-scale developments can become locked in to sub-optimal technology, but cannot afford to admit failure (Weyant, 2011). Wave and tidal stream technologies still require technology development and demonstration before being able to take full advantage of a demand-pull mechanism as the dominant form of incentive.

To rectify the imbalance requires the use of appropriate technology-push mechanisms, in conjunction with demand-pull mechanisms, to support the correct technological development that will allow technologies to reach a level of maturity in which they can be considered truly ready for array deployment and private sector investment. The requirement for further technology-push intervention and investment in R&D projects to stimulate adequate development of reliable technologies, at an appropriate and affordable scale, has been presented.

It has been demonstrated that the shift in focus towards marine energy demand-pull incentive mechanisms was introduced too early, with a focus on demand-pull providing insufficient leverage to enable the early multi-MW wave and tidal array projects to progress into the construction phase without significant further public sector intervention. Re-balance of policy support mechanisms and new policies are necessary to ensure guidance for investment and committed support from government meets with the aspirations of novel technology development, securing appropriate technology trajectories that, while requiring government intervention in the short term, can become economically sustainable in the long term.

7.5 Overall Conclusions

The hypothesis presented in Section 1.2 stated:

> "the dominant research, development and innovation environment being pursued within wave and tidal energy in the UK – rapid progression to MW-scale technology and development of multi-MW arrays – is not conducive to developing economically sustainable and reliable technology, nor facilitating the emergence of commercially viable wave and tidal energy technologies, in a timely and affordable manner."

Using techniques from innovation theory – diffusion of technology and learning theory – and outlining a specific comparison between historic policy mechanisms within wave, tidal stream, and on-shore wind energy technology development, this thesis has demonstrated that wave and tidal energy technology developers are pursuing a development pathway that is misaligned with routes that would offer strategically and economically superior pathways towards successful technology innovation and commercialisation.

This research has combined industrial ocean energy technology stakeholder engagement with analysis using innovation theory, and has identified the sub-optimal performance of the research, development and innovation environment within wave and tidal stream energy technology development. The hypothesis has been backed up by evidence within this research and overall conclusions can be summarised:

- Wave and tidal energy technologies are attempting to bypass a formative phase of technology development that has clearly been seen in the development of other energy sector technologies, thus omitting an essential step in proving availability, affordability, survivability and performance of ocean energy technology prior to technology up-scaling and commercialisation;
- There is a mismatch between the technological step being made by many device developers and the financial will or ability of the private sector investment community at this stage in technology development, leading to lengthy iteration cycles;
- The current range of technology SC, and the plausible LR suggested in leading industry reports create cost reduction trajectories with significant uncertainties. Minor deviations from optimistic deployment trajectories create substantial deviations in the overall learning investment requirements for wave and tidal energy.

- A targeted focus on the deployment of multi-megawatt technology is not an economically sustainable development environment – large investment costs are needed to realise each unit iteration, and with cost reduction predicated on substantial deployment, the range of uncertainty presents economic risks that very few investors are willing to take. This is not economically sustainable;
- The transition from technology-push to market-pull orientated support mechanisms has occurred prematurely within the wave and tidal energy sectors. 'Accelerated energy innovation' has resulted in an attempt to bring a technology that is not yet optimised into a market that is under-developed.

A number of factors, as discussed within this thesis, have contributed to the push for 'accelerated energy innovation', however this accelerated innovation has not resulted in the emergence of commercial ocean energy technology, nor has it established economically sustainable ocean energy technology development. The current development pathway is not optimised for most efficient use of available funding. The hypothesis has been demonstrated as being valid.

A mismatch between technological development and private sector financial will has developed, in part, through a perception that utility companies were to be the core customers of ocean energy technologies. Whilst this may be the case in the long-term (once an economically viable solution has been proven), the current nascent stages of wave and tidal energy do not meet with utility requirements for large scale power production at cost-competitive (or profit making) prices. An early focus on utility needs and requirements, reinforced by perceived investor and shareholder returns and economies of scale has pushed for rapid technology upscaling; the wrong product has been developed, and the product is not an affordable or attractive project for many of the early investors engaged with the ocean energy sector.

In addition, many of the UK's incentive mechanisms have stipulated the requirement for 'full-scale technology', which has almost universally been accepted to mean MW-class machines. Instead of seeking a minimum viable product from which to iterate and optimise in order to reach a solution, the wave and tidal energy sectors have been trying to get it right first time with MW-class 'utility scale' devices. Now that performance, cost, and development timeline realities do not meet utility expectations, utilities are withdrawing from the sector leaving a large number of technologies without a customer that is willing to take, or indeed is able to afford, the investment risk.

The formative phase of technology development will ascertain strengths and weaknesses within each technology design, but this phase requires more than a single unit prototype. A different approach to technology development is needed. Iteration is essential, but the current development pathway in the ocean energy sector does not facilitate ease of iteration. The ocean energy sector is failing to achieve rapid cycle times for subsequent product iterations – the chosen scale of product development has led to insurmountable economic requirements for many technology developers. Stimulating rapid cycle times is necessary to enable accelerated development of technologies, and those that are capable of achieving this are likely to overtake the current perceived industry front-runners.

This thesis has provided evidence that suggests that a paradigm shift is necessary within the wave and tidal stream energy technology development environment: in order to enable economically sustainable development of wave and tidal energy technologies, the focus cannot remain on large scale units alone, which are inherently costly and full of risk. It has been demonstrated within this body of work that smaller scale units can facilitate a larger number of unit iterations for a given cost, and technology development can take place within a more economically sustainable learning investment cost.

7.6 Technology Deployment or Continued Development?

Development and iteration costs more when attempting to innovate using large-scale technology. A transition in research, development and deployment environment is needed to move from a GW-focused deployed ocean energy capacity target to a unit iteration focused deployment trajectory. This research has concluded that the wave and tidal energy sectors need to consider smaller scale technology iteration, with evidence of larger numbers of unit iteration prior to a push for technology up-scaling and commercialisation, if economically sustainable development is to successfully take place.

To achieve this paradigm shift, a new policy framework is necessary in order to guide and re-direct the policies that will foster the emergence of an economically sustainable formative phase of technology development, and the subsequent deployment and diffusion of commercial technology.

7.7 Further Work

It is recognised, that although contributing significantly to the furthering of knowledge in the field of wave and tidal energy innovation and policy, there are improvements that could be made to the analysis contained within this thesis in order to enhance the applicability to the full life-cycle of ocean renewable energy technologies.

Firstly, Chapter 4 discussed 5PL curves with respect to unit deployment across a number of industries. For wave and tidal energy, the only at-sea installations in the UK have been demonstration units – no commercial technology has been installed to date. While suitable for making clear the dangers of going ‘too big too soon’, comparing demonstration units to commercially deployed technology in other sectors is not a direct like-for-like comparison. The vast majority of demonstration units in the wave and tidal sector to date could be considered as ‘outliers’, and are therefore unlikely to be representative of any future commercial technology trends.

Secondly, the analysis of the formative, up-scaling and growth phases of technology development considered technologies within a single market. Observation of trends within other countries to those investigated within this work could provide further insights into the requirement for iteration and deployment within other national, or even international markets. Information on global power plant deployments can be found in the Platt’s World Electric Power Plant Database (Platts, 2016), and could be a useful source of data for further work in this subject.

Thirdly, Chapter 5 considered only CAPEX costs in the learning investment model. This adequately allows the formative phase and its associated cost to be considered when technology is at the early stages, as technology within a formative phase is unlikely to have the same life expectancy as a commercial unit – therefore a CAPEX only study is valid for considering rapid iteration times without commercial-level technology performance. However, an improved model could also account for operational costs in the lifetime of the unit. Furthermore, additional improvement could be made by accounting for growth in unit scale; the current model maintains a consistent technology scale throughout the deployment model. In reality, upon successful proving and demonstration of technology in the wave and tidal energy sector, it is likely that the technology will be able to increase in scale to unlock OPEX cost efficiencies, and device or array performance improvements. Reflecting this unit-level up-scaling within the learning investment model as a growth factor in unit scale would provide an enhancement to this work, and could be considered as a valuable piece of further work that would complement and enhance this research activity.

Fourthly, the cost of offshore wind is anticipated to fall as continued deployment progresses. This presents a moving benchmark that wave and tidal energy technologies may be required to meet. Adapting the learning investment model to account for this offshore wind cost-reduction benchmark may improve the estimation of learning investment requirements, as they are likely to be higher than those currently suggested by the model due to the limitations associated with the existing fixed-cost benchmark.

Chapter 8

Evidence for Policy Reform

8.1 Chapter Introduction

The purpose of this chapter is to summarise evidence justifying the need for new policies to support continued wave and tidal energy technology development. The misalignment between policy or economic stakeholder expectations and technology development, which has been identified within the context of this thesis, needs to be addressed by new policies if economically sustainable development of wave and tidal stream energy technologies is to be achieved. A policy framework is a set of principles and long-term goals forming the basis of rules and guidelines to give overall direction to the technology trajectory and innovation pathway of technology development within the wave and tidal energy sectors. By drawing upon the results presented within this thesis, the recommendations for new policies offers a new perspective on what is required to enact a paradigm change within the ocean energy research, development and innovation process. This is necessary in order for the nascent wave and tidal energy sectors to foster successful formative development and become a successful contributor to the future energy mix.

Appropriately defined long-term policies, focused on the engineering development needs of step-change innovation within a larger number of unit iterations rather than on the short-term revenue generation aspirations of accelerated innovation, should receive greater attention if the wave and tidal energy sectors are to successfully navigate through a formative phase of development in a cost effective manner.

8.2 Enabling Economically Sustainable Development of Ocean Energy Technologies

This research has presented alternative strategies to enable the emergence of economically sustainable development of wave and tidal stream energy technologies, with an aim of allowing these technologies to achieve success as an established power generation technology within the global energy mix. The fundamental shift in development strategy requires technology trajectories that undertake appropriately scaled research and development, whilst recognising the need for technology to progress iteratively through a formative phase of development prior to widespread build out and commercialisation; it requires technology trajectories that recognise the economic risk and uncertainties associated with over-aggressive unit up-scaling within a formative phase of technology development. This formative phase needs to be affordable both to private sector investors, who will be required to enable this niche technology to achieve its commercial aspirations beyond early stage deployment, and to governments, who will be required to commit significant (and perhaps long-term) research and development funding.

The long term goal and objective is no different to what it has been since the dawn of wave and tidal energy development – extracting useful energy from waves and currents – but the manner in which this goal is to be pursued must change from what has been the mindset of much of the industry to date.

The future of the wave and tidal energy industries rest upon the ability to adopt a paradigm change in the research, development, and innovation process, and the way in which commercialisation of wave and tidal energy technologies are pursued. The following sections describe the necessary transition in perspective, a change in paradigm that, based on the results of this research, could re-align the industry on a route towards economically sustainable technological research, development and innovation.

8.3 Recommendations and Solutions for Policy Guidance

In order to ensure economically sustainable development of wave and tidal stream energy technologies, appropriate policies must oversee technology progression through a formative phase of development. Iteration and optimisation must be encouraged – present day technology is not optimised in terms of performance or cost, therefore the need for multiple unit iterations must be recognised. This formative phase could take tens, hundreds, or perhaps even thousands of devices prior to converging upon an eventual front-runner – the cost of which has a very high risk of being prohibitive under the previous research, development and innovation environment.

Specific objectives and attributes for a new policy framework can be considered to encourage and incentivise technology development at a scale in which unit iteration is affordable, timely, and realistic:

- Enable appropriate technology trajectories and ensure prevention of over-expensive risk-intensive technology trajectories;
- Encourage early stage experimentation and optimisation during the formative phase of development – at appropriate technology scale;
- Encourage unit iteration prior to unit-level up-scaling, but ensure that technology *is* scalable;
- Facilitate Darwinian Evolution;
- Ensure granular technology development through multiple examples of unit iteration of modular and dispersed technology;
- Support the identification and utilisation of niche market opportunities;
- Address the imbalance between technology-push and demand-pull support mechanisms;
- Recognise that the costs of bringing ocean energy technologies to commercialisation are beyond the capabilities of one country alone – a mandate for international R&D coordination exists.

The new policies must enable design convergence around optimised solutions and shakeout of technology prior to diffusion of innovation and industry level up-scaling. Requirements for successful progression through a formative phase of development include an increased number of unit iterations, a decrease in cost per unit iteration, and a decrease in time taken per unit iteration. The new policies must encourage and stimulate iteration and optimisation of technology which, under appropriate metrics, can be monitored to ensure that continued positive progression is sustained. Unit and industry level up-scaling for technologies can commence once successful formative development has resulted in an optimised technology.

Three fundamental improvements are needed over the existing research, development, and innovation environment, and must be prioritised in future policy guidelines.

1. A clear strategic focus on assisting the appropriate technologies through correctly judged development stages in which to demonstrate and prove technology availability, survivability, affordability and performance prior to progression towards commercially focused large-scale unit deployment, operation and revenue generation;
2. An economically feasible and sustainable pathway and trajectory for development and deployment – consuming significantly smaller quantities of public funds per project, offering superior cost-effectiveness in iteration;
3. An improvement in private sector investment confidence, through visible performance proving over a larger number of units – therefore ensuring that the baseline and benchmark technology performance is based upon more than just the statistic of one that exists within many technology developers to date.

8.3.1 Enable appropriate technology trajectories and ensure prevention of over-expensive risk-intensive technology trajectories

The research carried out within this thesis has demonstrated the lack of a formative phase of development in wave and tidal energy prior to substantial unit up-scaling. This trajectory has been actively encouraged by investors, stakeholders, and policymakers. However, the cost and risk associated with iteration at large-scale has created a shortfall in funding, and an inability for many projects to reach financial close. The step taken by technology development is greater than the financial will or ability of the investment community. Inappropriate technology trajectories should not be incentivised, and there are warning signs showing strains on technology development within the wave and tidal energy sectors to date. Up-scaling and market diffusion should not be used as a means to stimulate technology development.

Up-scaling of technology and market diffusion should only be supported when technology has successfully demonstrated improved or increased capability and performance, however, up-scaling and market diffusion should not be used as a means to stimulate technology development. New policies should encourage and incentivise affordable, timely, and realistically achievable multiple unit deployment and unit iteration – metrics which have more chances of success using appropriate mechanisms directed at smaller-scale technology within the formative stages of development.

8.3.2 Experimentation and optimisation during the formative phase of development

A formative phase of technology development has been consistently demonstrated to involve a period of experimentation using small-scale units prior to up-scaling and diffusion of technology. There is no known example of energy technology that has achieved commercial success after only a handful of unit deployments, yet this is what wave and tidal stream energy technologies have been trying to achieve to date.

Experimentation is costly in the conceptual stages of development, and initial costs do not necessarily reflect the eventual cost of any commercial product developed. However, cost can be mitigated in the iterative formative phase of development by choosing to iterate at a scale where the level of investment required could be considered commensurate with the risks. Large scale technology deployments have resulted in costs exceeding tens of millions of pounds. Achieving multiple iterations at this scale is not economically sustainable and an alternative must be found.

Much design diversity still exists within the wave energy sector. To fund each and every design type to multi-MW-scale array deployment is inconceivable. A significant part of the formative phase of development is to iterate out any design flaws and weaknesses, and to reach a point where consolidation on optimal solutions emerges. Shakeout of the industry will see acquisition of smaller players, and attrition of weaker technology solutions. Only the successful emergent technologies following a period of shakeout should be in a position to gain confidence from investors for multi-million pound unit and industry level up-scaling.

While the tidal energy sector has largely seen convergence around horizontal axis turbines, there still exists much diversity in the selection of sub components, or foundation/mooring solutions. Much experimentation and optimisation could be required in order to ascertain the most favourable selection and arrangement of systems or sub-components. Direct experimentation with multiple permutations of each option are unlikely to be strategically realistic or economically feasible using MW-scale technology, but iteration at kW-scale would unlock the possibility for these experiments to take place within much more modest levels of expenditure.

New policies must encourage iteration and experimentation at appropriate cost and scale. Experimentation is not economically sustainable using MW-scale technology, and so apposite judgement would need to be made on the scale of technology that enables more affordable experimentation.

8.3.3 Unit iteration prior to unit-level up-scaling

In tandem with encouraging experimentation and optimisation lies the need to demonstrate success over a range of units – not just using a single unit upon which to base all claims made. A jump from single device to multi-MW array should only occur once sufficient demonstration of performance, affordability, availability, and survivability has taken place at a unit level. Unit iteration prior to up-scaling will allow the utilisation of feedback loops within the design process during the formative phase of development, prior to active engagement with more advanced projects.

Early stage burn-in failures and teething-problems should be identified during the formative iteration stage. Removal of weak links in design at small scale will make iteration affordable. Re-design and iteration at large unit scale is costly and expensive, and has not been suitable for facilitating rapid iteration timescales or learning.

New policies should encourage unit iteration prior to unit level up-scaling, such that design flaws, challenges, and issues are identified before more significant capital investment commitments are made. With increased iteration, greater confidence in design will be established as an optimsed solution will be reached before more technically and economically challenging projects are attempted. However, it should also be made clear that any technology considered should also be scalable to MW capacities – unit capacity growth in the medium to longer term will be necessary.

8.3.4 Facilitate Darwinian Evolution

Whilst experimentation is to be encouraged, continued funding of weak technology should not be. Where improvement in performance metrics is not sustained there should be an identified need to pivot the technological development trajectory; continued funding of technologies that are "locked-in" to sub-optimal designs and failing to meet metric objectives should be prevented.

Attrition of technology is to be expected. Similarly, during a shakeout stage in development, technology may be consolidated through the acquisition of smaller companies by larger firms. Policies should seek consolidation and shakeout of technology as a precursor to industry-level up-scaling and diffusion of technology. Accepting that not all funded projects will meet with success is integral to this, and so, as previously discussed, iteration must be carried out at a scale more affordable than the historic technology trajectory, where the cost of a failure does not bankrupt an industry.

8.3.5 Multiple examples of modular and dispersed technology

The outcome of innovation and early stage experimentation is inevitably uncertain. The uncertainty of technological development in wave and tidal stream energy does not leave room for putting "all the eggs in one basket" financially, technologically, or geographically.

Governments must not be tempted into picking winners in order to accelerate innovation. There is a requirement that iteration and experimentation is completed across a number of technologies and across a range of geographic possibilities. A portfolio of experimentation will be required in order to increase the chances of success and mitigate the consequences of failure.

8.3.6 Identification and utilisation of niche market opportunities

While the end goal of technology development in the wave and tidal stream energy sectors may be the commercial generation of electricity for distribution into national grid infrastructure, the road to achieving such a goal can also encapsulate a number of niche market opportunities. Examples in the wave and tidal stream energy sector include exposed aquaculture (i.e. aquaculture sites located in more energetic and less sheltered waters), or replacing diesel generation in remote off-grid communities – examples that are particularly well suited to smale-scale applications. The level of cost competitiveness and magnitude of capacity requirement is different than for grid/utility power generation, therefore niche markets may become early adopters of technology.

Policy must recognise the importance of niche markets in establishing potential revenue generation from implementation of early unit deployment. In addition, the role of niche markets in establishing and garnering private sector involvement should not be overlooked. Whilst niche markets may not offer the full attraction of utility scale power generation, it offers a stepping stone in terms of deployment demonstration, and the initiation of a market from which to grow. Niche markets should therefore be encouraged, and policy support mechanisms for such applications clarified.

8.3.7 Address the imbalance between technology-push and demand-pull support mechanisms

A range of policy support mechanisms will be needed in order to successfully navigate the transition from invention to innovation, and then from innovation to diffusion. The timing of these policy mechanisms plays an important role. Premature withdrawal of technology-push mechanisms risks under-developed technology that fails to reach sufficient levels of development or maturity; the private sector may not have the appetite for risky investment under these conditions, and development of technology will stall. Premature introduction of demand-pull mechanisms could result in over-optimistic market conditions for an under-developed technology. Technology then has to “accelerate innovation” inappropriately to be seen to meet the ‘market’ demand. Delayed introduction of demand-pull mechanisms could increase the time lag between initial investment and subsequent returns associated with successful commercial application – making the private sector reluctant to invest (Nemet, 2009).

There are two pinch points (or ‘valleys of death’) in which failures amongst developing technologies are most commonly experienced: firstly, between successful innovation and commercial scale prototype demonstration; secondly, between successful prototype demonstration and large scale build out or diffusion (Weyant, 2011).

The current focus of ‘commercial-scale’ development (devices in the order of 1MW) has resulted in a need for extensive investment in order to continue development. Technologies of this scale are inherently costly, and policy support mechanisms have provided the means for demonstration projects to take place in locations such as EMEC. However, most of these MW-scale demonstration projects are no longer in the water, short term projects with no successor technology to carry out continued R&D. The next step for many of these technology developers is multi-MW arrays, however, there are few who have been able to secure the necessary investment in order to allow this subsequent deployment to take place. Thus increased policy support is necessary in order to secure the further development of technology, resulting in large public sector expenditure. Without rapid cost reduction, this current approach cannot continue to be sustained – particularly if the levels of unit deployment prior to successful technology shakeout extends into hundreds of units.

An effective policy support mechanism requires policies that are consistent, and that provide long-term confidence. Thus policies must be able to continue to impact research and development, and transition through and beyond the two 'valleys of death' identified. Policy makers seeking to support development of innovative technology must ensure that the policies that are introduced can be sustained over a prolonged period of time.

Ocean energy policy must recognise the need for consistent long term support that can be flexible to adapt to changing needs and requirements of a fledgling industry, providing appropriate policy resource for both technology development and technology deployment – ensuring that markets are created and grown. Unstable or unpredictable policy frameworks can have a large impact on the 'bankability' of a project, therefore, it is important that ocean energy policies can provide certainty regarding the R&D support during formative phases of development, ensure the growth of niche and then mature markets for technology deployment, and provide guaranteed annual revenues that can be expected from a project over its life once unit-level and industry-level growth becomes appropriate. Given the current technological uncertainty, a policy framework cannot be overly biased towards demand-pull mechanisms. New policies must be consistent in confirming the long term nature of the support mechanisms (both in terms of R&D support and in terms of production subsidies) in order to instill confidence within private sector investors. Furthermore, clarification of the technology scale at which this framework is financially viable and economically sustainable would also be advisable. As investigated within earlier chapters of this thesis, long-term support for MW-scale technologies does not appear to be an economically feasible or sustainable approach, with technologies in the region of 100kW presenting a more economically plausible alternative.

8.3.8 Recognise that the costs of bringing ocean energy technologies to commercialisation are beyond the capabilities of one country alone.

This research has demonstrated the economic impact of deviation away from optimistic deployment and cost reduction trajectories. The uncertainties at this stage in development are too great to allow private sector investment confidence, and therefore positive political will is an essential ingredient in allowing the formation of wave and tidal energy technologies that can realise the ambitions of the ocean energy sector.

While development is taking place locally in a number of countries worldwide, this research has suggested that the cost of developing and deploying wave and tidal technology until it reaches a level of cost competitiveness with more mature alternatives such as offshore wind, will be a level of investment that one country alone will not be able to support – a mandate for international R&D coordination exists. The desire to see ocean energy technologies play a key part in the electricity mix exists in a number of countries, however the level of cooperation and collaboration at research, development, and deployment levels lacks the structure that would be able to provide a mechanism for pooling sufficient resources from each country into a common development framework.

If the wave and tidal energy sectors are to achieve their goal of commercialisation, then the development must involve international collaborative activity and pooling of resource, otherwise there is a significant risk that the burden of R&D and deployment costs become greater than the capability of the established political stakeholders can bear.

In order to contextualise the learning and total investments discussed within this thesis, they would not be required as a one-off payment, but would take place over a number of years to allow project build out. This investment could, for example, comprise of much smaller annual contributions spread over a 20-year period. This can then be seen to be only a small fraction of the total funding devoted to strategic infrastructure projects across a number countries across the globe.

8.4 Impact

This thesis has focused on three core themes of technology, economics and policy. Within each of these topics, this research has presented unique and novel contribution that has furthered understanding within the field of wave and tidal energy.

If the innovation process requires the optimisation of an invention prior to the emergence of a comercially viable technology, then it is plausible that many iteration attempts will be required before the invention is perfected (or, perhaps more appropriately, a minimum viable product is reached). In that respect, the variable of interest is not time, nor cumulative installed capacity; it is the number of iterations required between first deployment and eventual unit up-scaling, or between the first unit deployment and the subsequent growth of the industry.

This thesis has considered the changes in unit-level and industry-level growth of energy sector technologies with respect to unit deployment, as opposed to observing trends over time. While time based studies are useful for historic analysis, they cannot be used as a means to forecast technology development. Deployment based studies have revealed the considerable unit deployment numbers that were achieved prior to unit and industry level up-scaling in a number of energy sector technologies. Historic pathways have demonstrated consistency: starting with small unit scales, and exhibiting large numbers of unit deployments within a formative phase of development. Up-scaling at both unit and industry level has only followed after a formative phase.

This research presents the first time that this has been discussed with a more specific application within the field of wave and tidal energy. This research challenges the view of the mainstream tidal and wave energy sector that suggests that large MW-scale technologies are imminently needed in order to bring confidence in the capability of the ocean energy sector becoming a commercially viable entity. This research has provided evidence to suggest that many hundreds of unit iterations could be required prior to the establishment of a sound formative phase of technology development – a value much higher than the current expectations of many early stage technology developers.

Theoretical cost reduction curves and the effects of learning have long been discussed within the field of ocean energy, and cost reduction trajectories presented in industry based reports. However, little focus has been given to the implications and effects of small perturbations in input parameters on the overall cost reduction process. In addition, industry reporting has tended to use very optimistic deployment and cost reduction trajectories. Using single factor learning curves to build a cost reduction model, this research has for the first time presented explicitly the effects of minor changes to input parameters on the overall investment requirements for the deployment of ocean energy technologies.

A sensitivity analysis of the key parameters of SC, LR, and CSCR have been presented within this work, identifying the financial implications of deviation from optimistic input assumptions. The analysis carried out for this thesis has created 14,200 plausible scenario possibilities, and has demonstrated learning investments ranging from tens of millions to tens of billions of pounds. The uncertainties in ocean energy cost reduction trajectories represent total investment and learning investment cost variations of four orders of magnitude. In addition, a probabilistic cost model was created to enable higher fidelity learning investment cost modelling than has been carried out within the wave and tidal energy sector to date.

This research has considered a number of metrics as a means of identifying appropriate transitions from technology-push to demand-pull orientated support mechanisms. The research has clarified the disparity between the development maturity of wind energy technology and wave/tidal energy technology with regards to the introduction of demand-pull dominated support mechanisms. The mainstream wave and tidal energy technology development pathway has resulted in an attempt to bring a technology that is not yet optimised into a market that is under-developed. There is a mismatch between the level of technology development and the policy aspirations.

By bringing together the findings from techno-economic and policy analysis carried out within this thesis, recommendations have been made for new policies that can support the transition towards economically sustainable development of wave and tidal stream energy technologies. What perhaps may have appeared to be broad and diverse topics has been seen to come together in a single axis – a set of recommendations for policy, to enable more appropriate stewardship of funding allocated towards ocean energy technologies.

8.5 Concluding Remarks

The work presented in this thesis has identified that the wave and tidal stream energy technology trajectory has attempted to bypass a formative phase of development, and there exists a very high risk that continuation along a research, development and innovation environment that focuses on rapid deployment of pre-commercial large MW-scale technology will be economically unsustainable, failing to bring commercially successful ocean energy technology in an affordable and timely manner. An alternative pathway has been presented, one that is more appropriate for formative phase technology development, and one that offers a higher probability of allowing economically sustainable technology development – utilisation of kW-scale technology. More modest unit scales in the formative stages of development, in the region of 100kW will allow cost-effective unit iteration, and increased opportunity to iterate and optimise through learning by doing, facilitating technology shakeout prior to unit-level and industry-level growth. Only through a transition in research, development and innovation environment will the wave and tidal stream energy sectors be able to attain the goal of economically sustainable development of technology, enabling greater probability of ocean energy technology being able to provide a significant contribution to the global energy mix in an affordable and timely manner.

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Appendix A

Publications

Journal Papers:

- MacGillivray, A., Jeffrey, H., Winskel, M., and Bryden, I. Innovation and cost reduction for marine renewable energy: A learning investment sensitivity analysis. *Technological Forecasting and Social Change, Volume 87, pages 108-124*, 2014, ISSN 00401625, doi: 10.1016/j.techfore.2013.11.005.
- MacGillivray, A. and Jeffrey, H. The importance of iteration in technology development: Impact on the wave and tidal stream energy research, development and innovation paradigm. *Energy Policy, Volume 87, pages 542-552*, December 2015, doi: 10.1016/j.enpol.2015.10.002.

Conference Proceedings:

- Sankaran Iyer, A., MacGillivray, A., Couch, S., Winskel, M., Jeffrey, H., Wallace, R., Bryden, I. Analysis of tidal current energy scenarios in UK and Capital cost of energy. *Proceedings of the 1st Asian Wave and Tidal Energy Conference, Jeju Island*, 2012.
- de Andres, A., MacGillivray, A., Identifying risk and Uncertainties – Pathways towards a Lower LCOE in Marine Energy. *Proceedings of the 5th International Conference of Ocean Energy, Halifax (Canada)*, 2014

Reports:

- MacGillivray, A., Jeffrey, H., Hanmer, C., Raventos, A., Ocean Energy: State of the Art. *SI Ocean Project Deliverable*, 2012.
- Hanmer, C., MacGillivray, A., Jeffrey, H., Raventos, A., Ocean Energy: Cost of Energy and Cost Reduction Opportunities. *SI Ocean Project Deliverable*, 2013.
- MacGillivray, A., Jeffrey, H., Hanmer, C., Magagna, D., Raventos, A., and Badcock-Broe, A., Ocean Energy Technology: Gaps and Barriers, *SI Ocean Project Deliverable*,

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- MacGillivray, A., Jeffrey, H., Raventos, A., Chozas, J., Nielsen, K., Previsic, M., Aderibigbe, D., International Levelised Cost of Energy for Ocean Energy Technologies., 2015. Available online: http://www.ocean-energy-systems.org/news/international-lcoe-for-ocean-energy-technology/?source=newsletter

Appendix B

Monte Carlo Simulation Model for Large Scale Technology Deployment

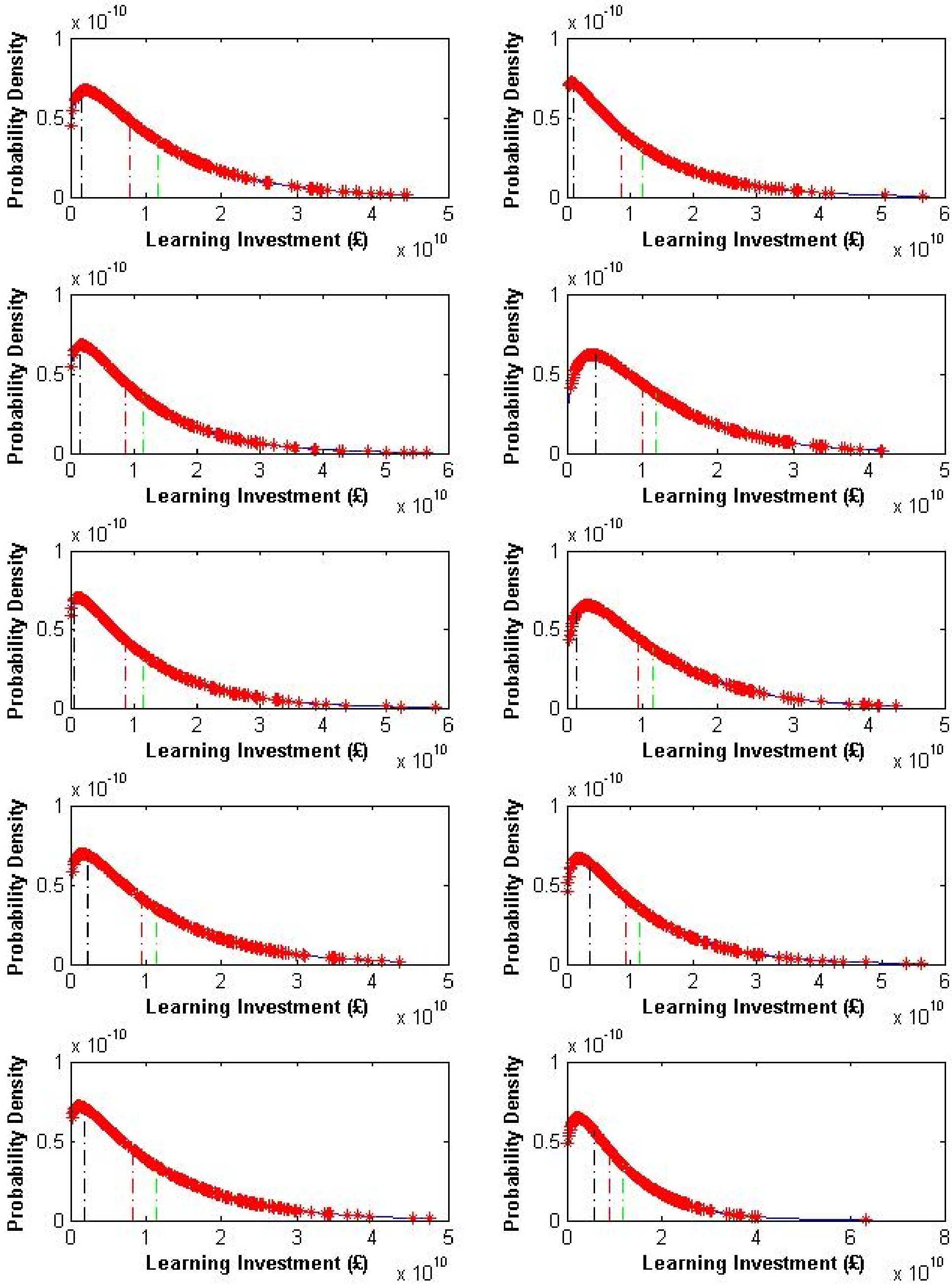

Figure B.1: PDF of Learning Investment for all 10 runs of the Large Scale Technology Simulations.

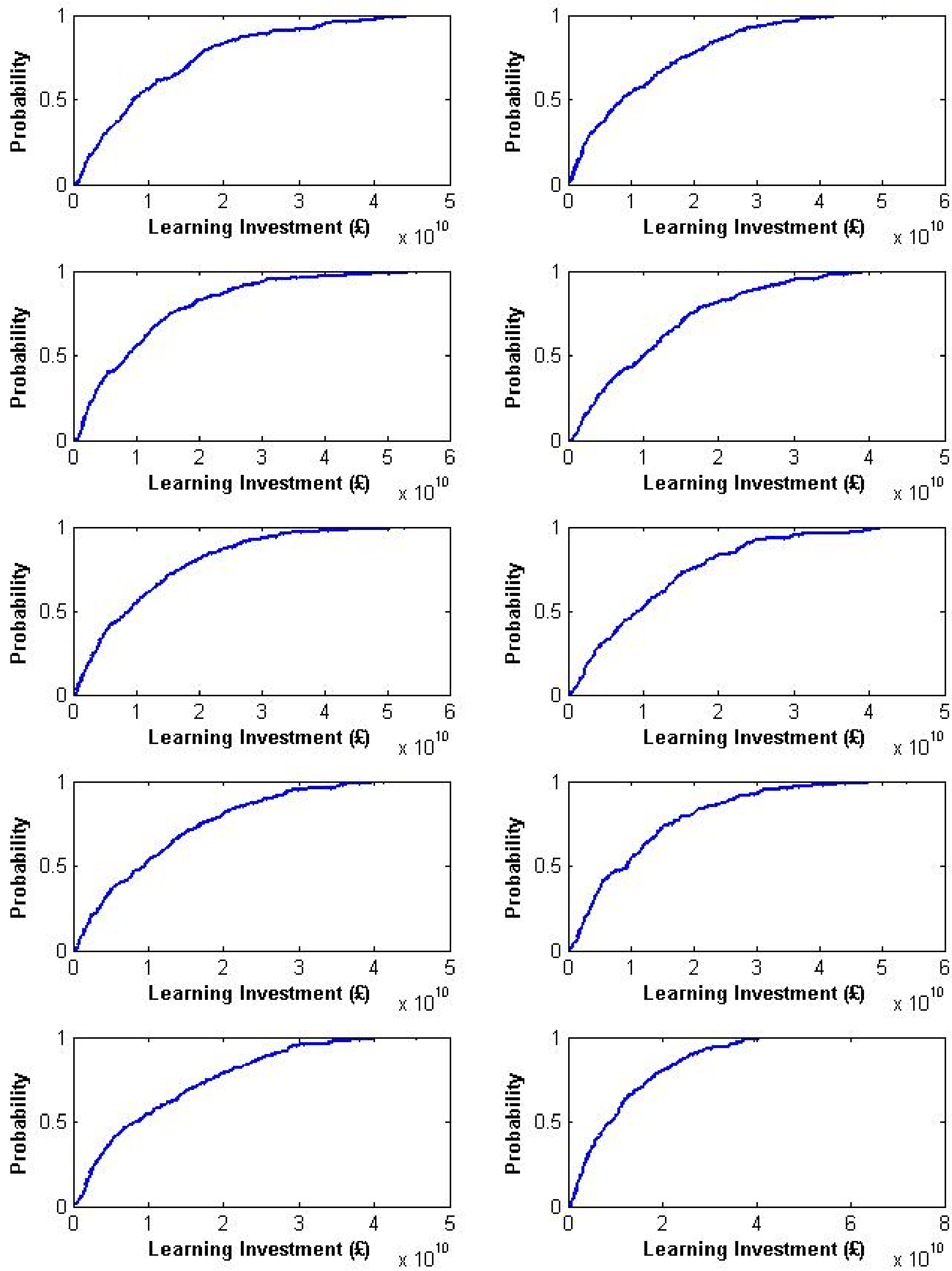

Figure B.2: CDF of Learning Investment for all 10 runs of the Large Scale Technology Simulations.

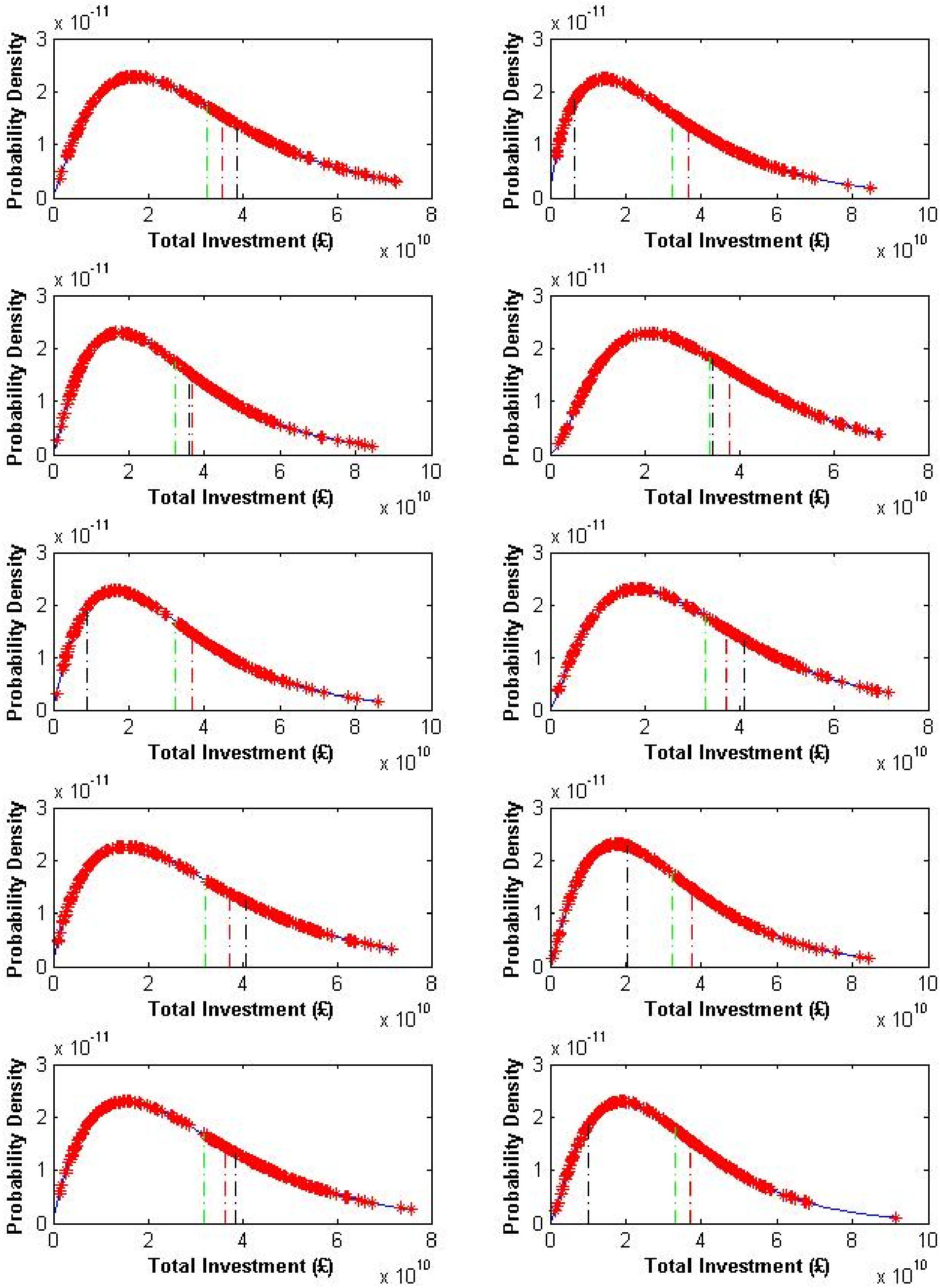

Figure B.3: PDF of Total Investment for all 10 runs of the Large Scale Technology Simulations.

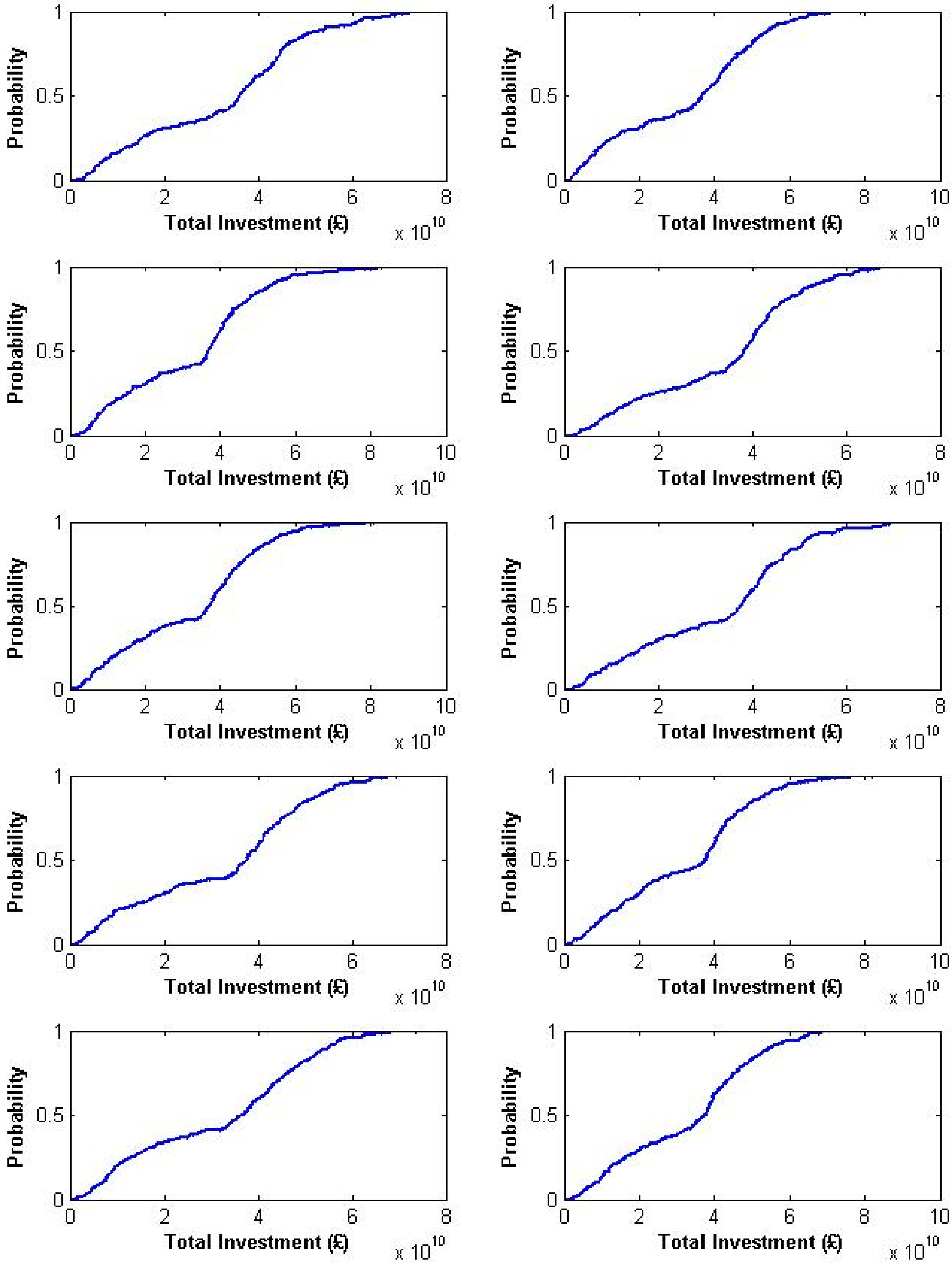

Figure B.4: CDF of Total Investment for all 10 runs of the Large Scale Technology Simulations.

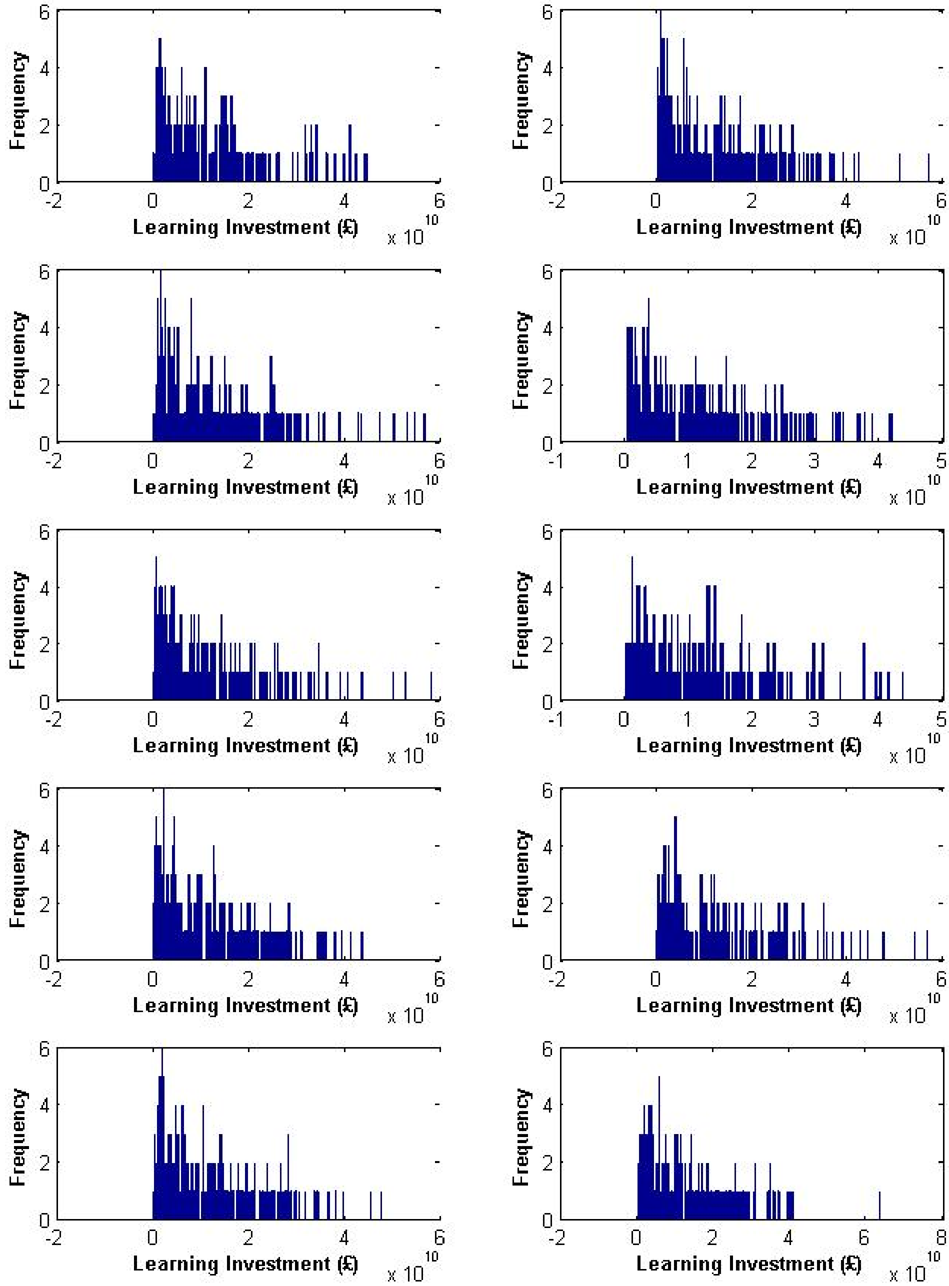

Figure B.5: Frequency Occurrence of Learning Investment for all 10 runs of the Large Scale Technology Simulations.

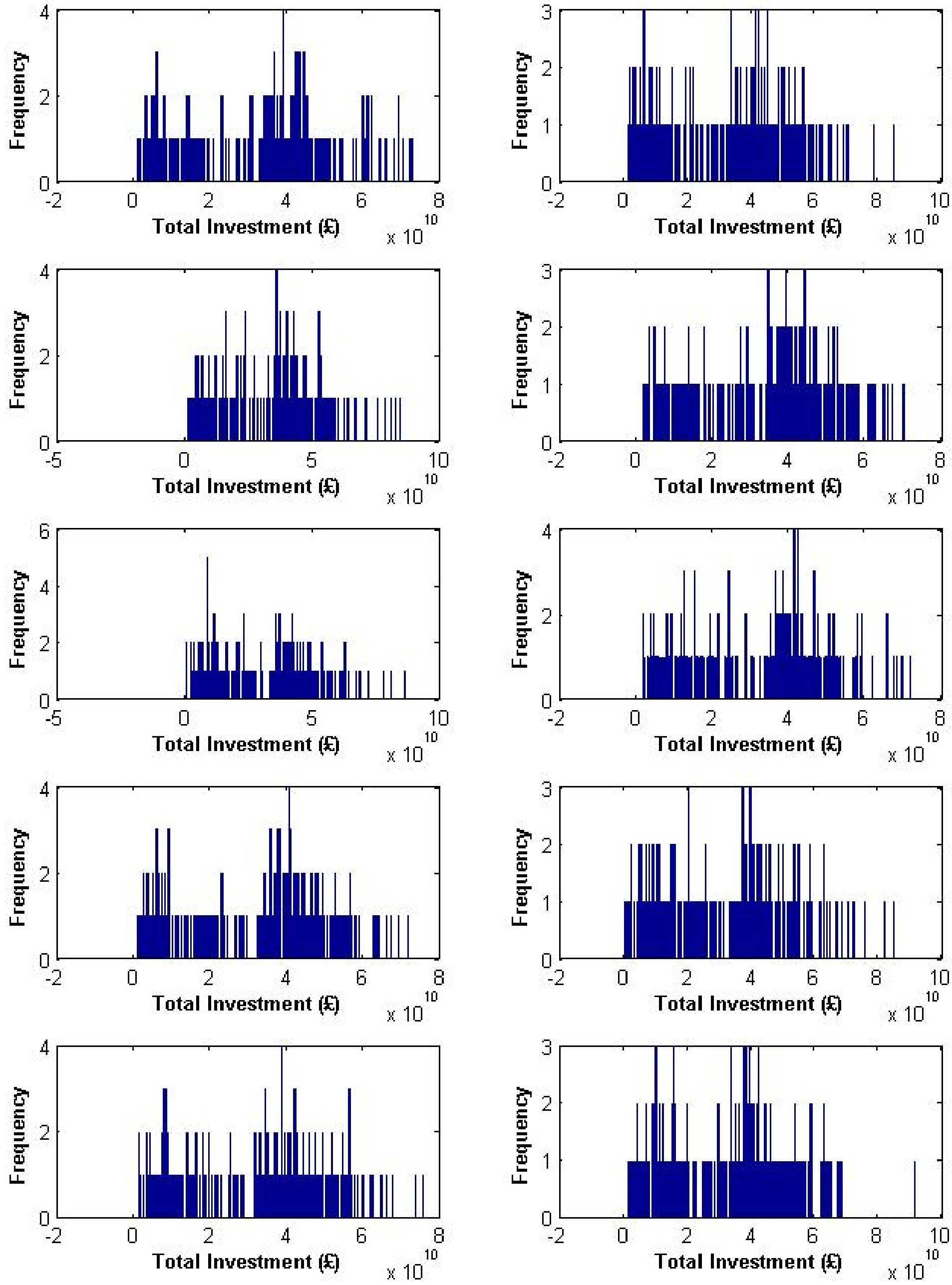

Figure B.6: Frequency Occurrence of Total Investment for all 10 runs of the Large Scale Technology Simulations.

Appendix C

Monte Carlo Simulation Model for Small Scale Technology Deployment

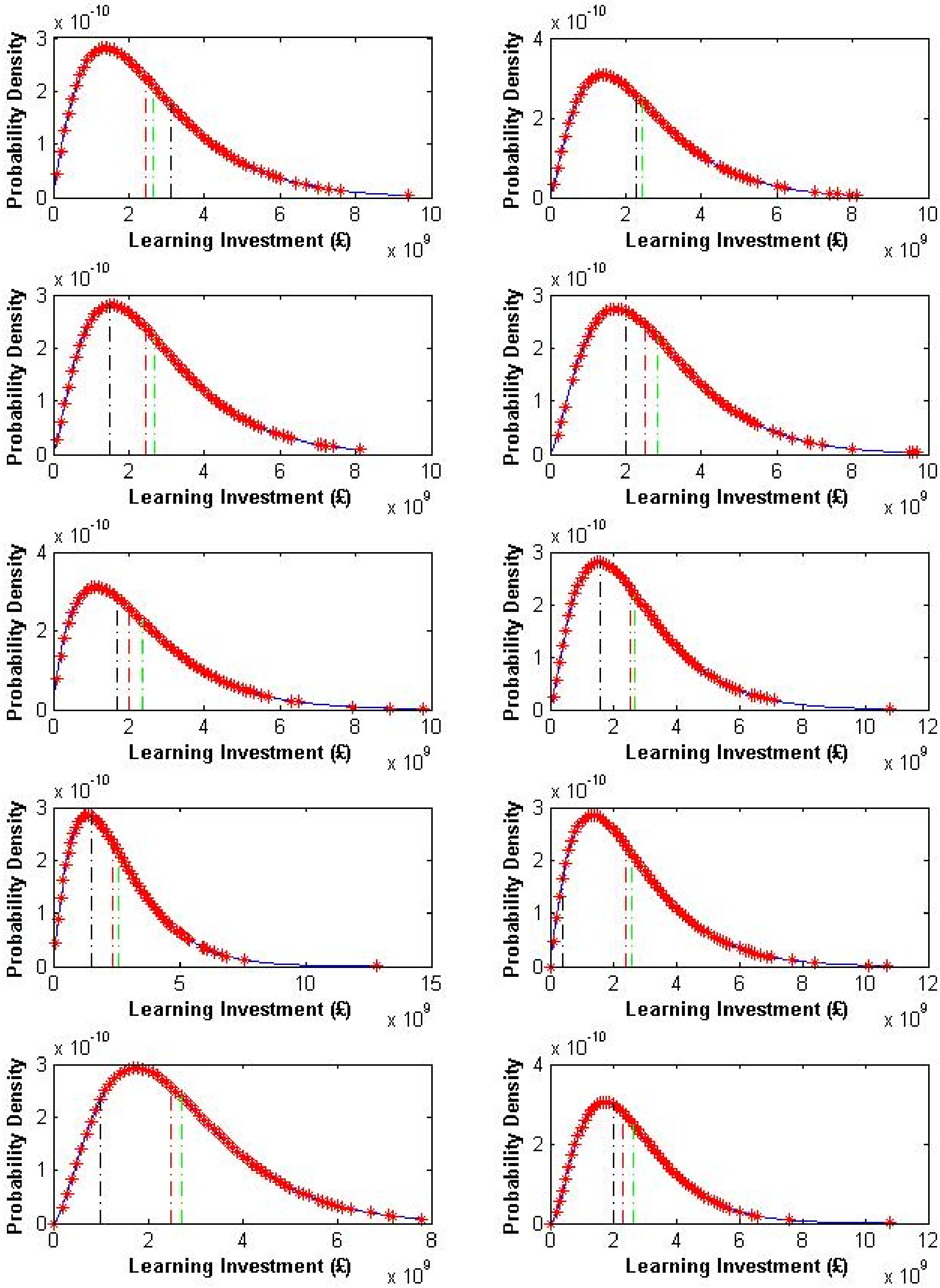

Figure C.1: PDF of Learning Investment for all 10 runs of the Small Scale Technology Simulations.

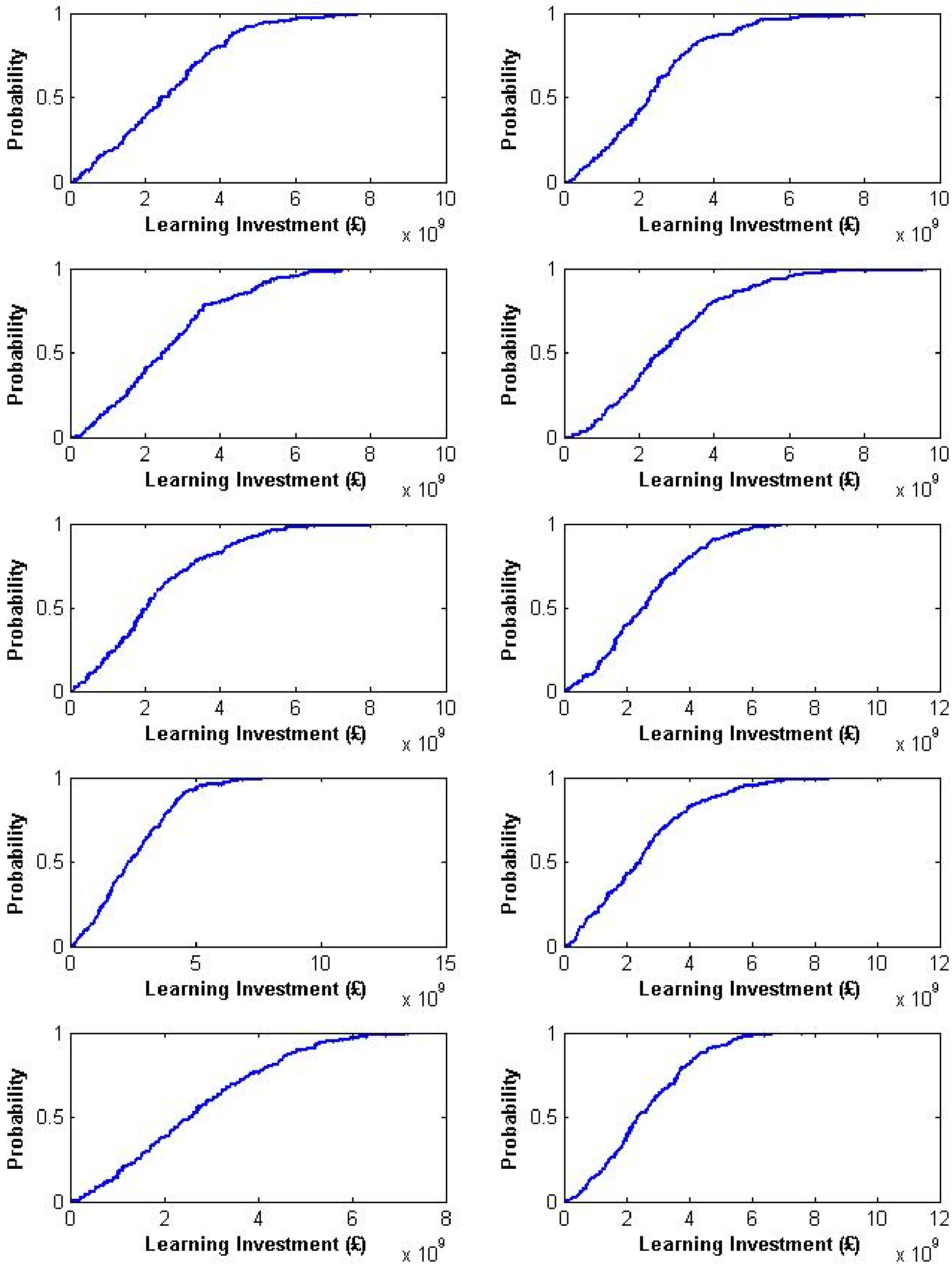

Figure C.2: CDF of Learning Investment for all 10 runs of the Small Scale Technology Simulations.

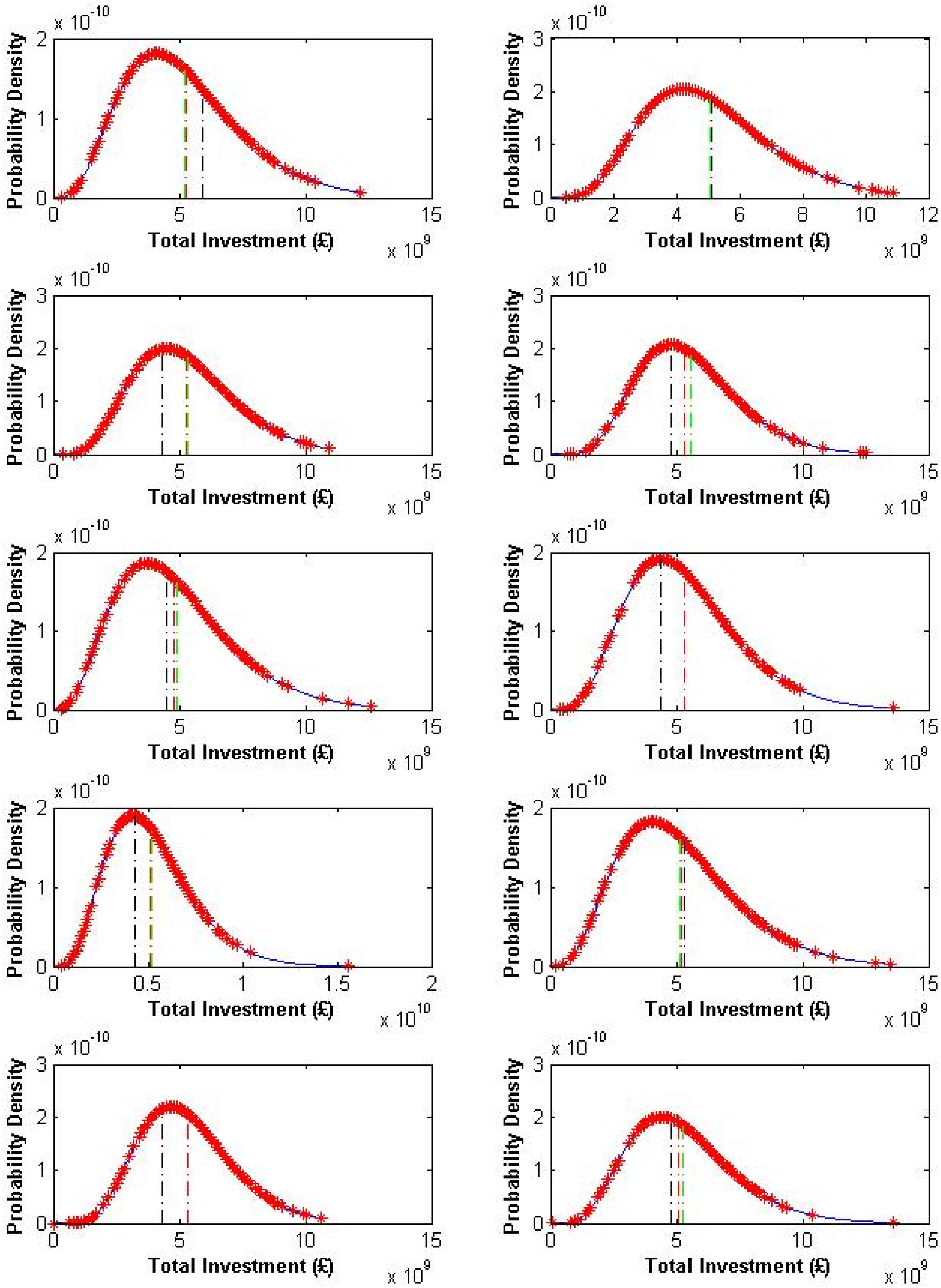

Figure C.3: PDF of Total Investment for all 10 runs of the Small Scale Technology Simulations.

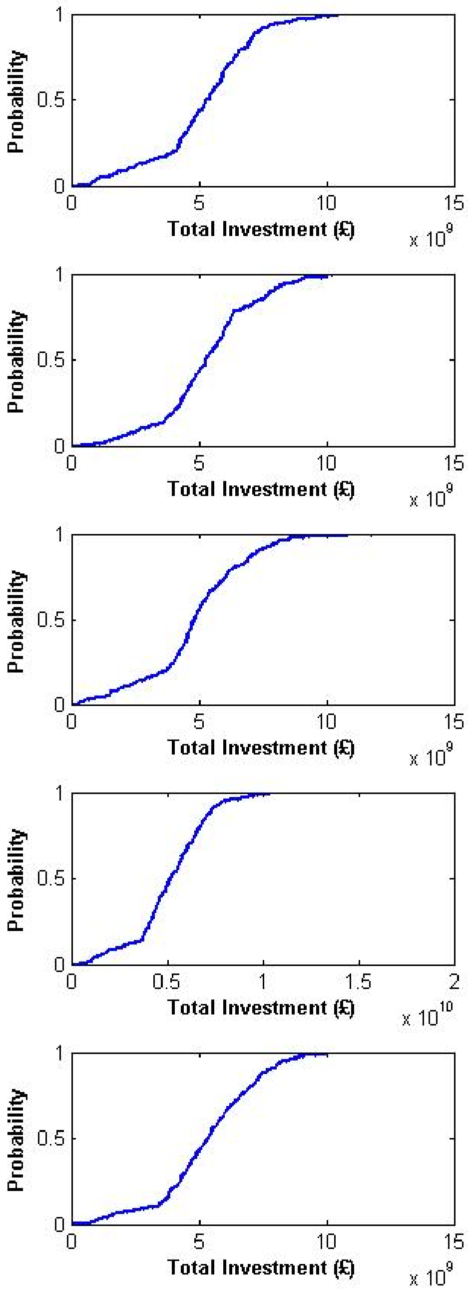

Figure C.4: CDF of Total Investment for all 10 runs of the Small Scale Technology Simulations.

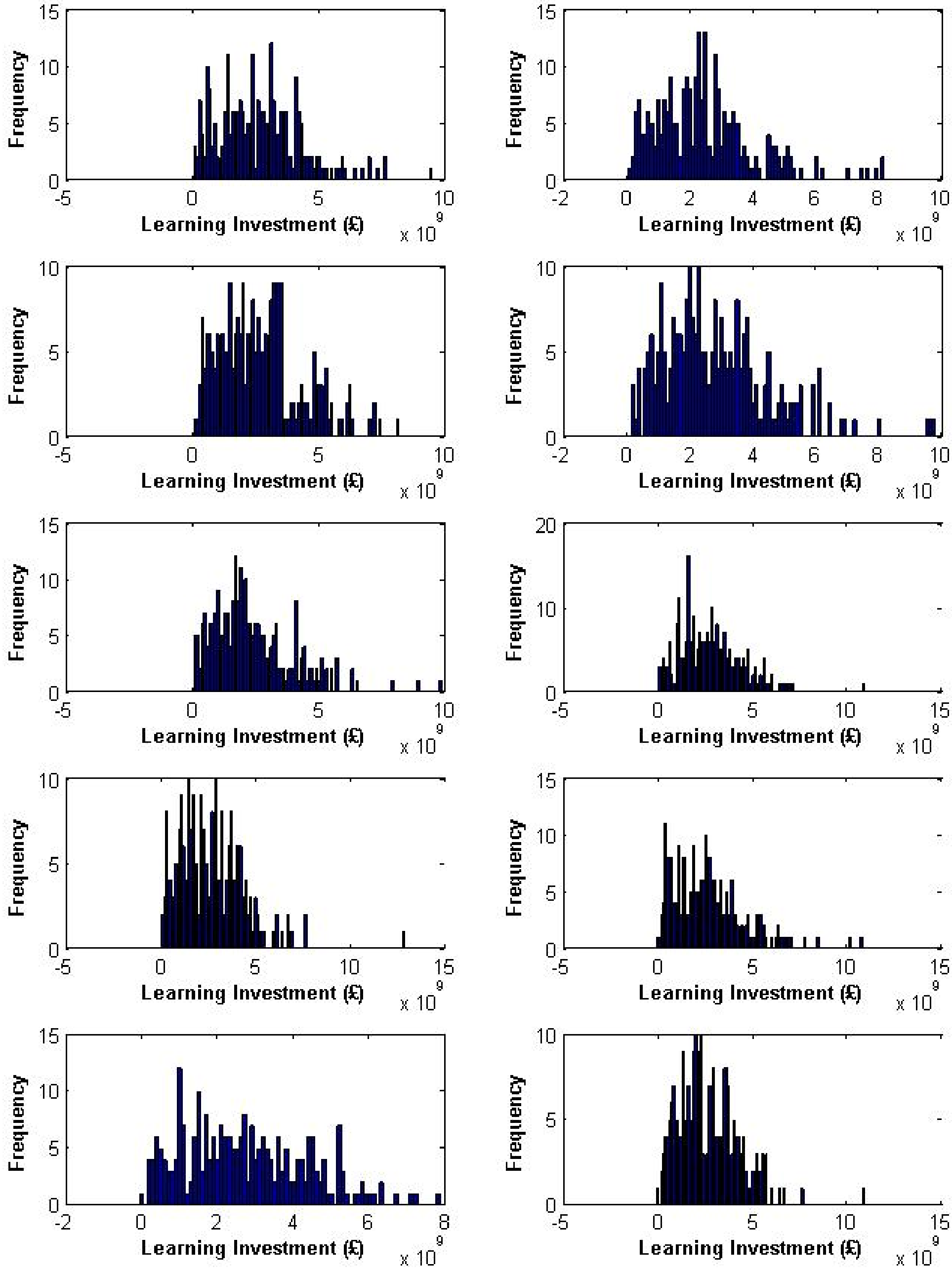

Figure C.5: Frequency Occurrence of Learning Investment for all 10 runs of the Small Scale Technology Simulations.

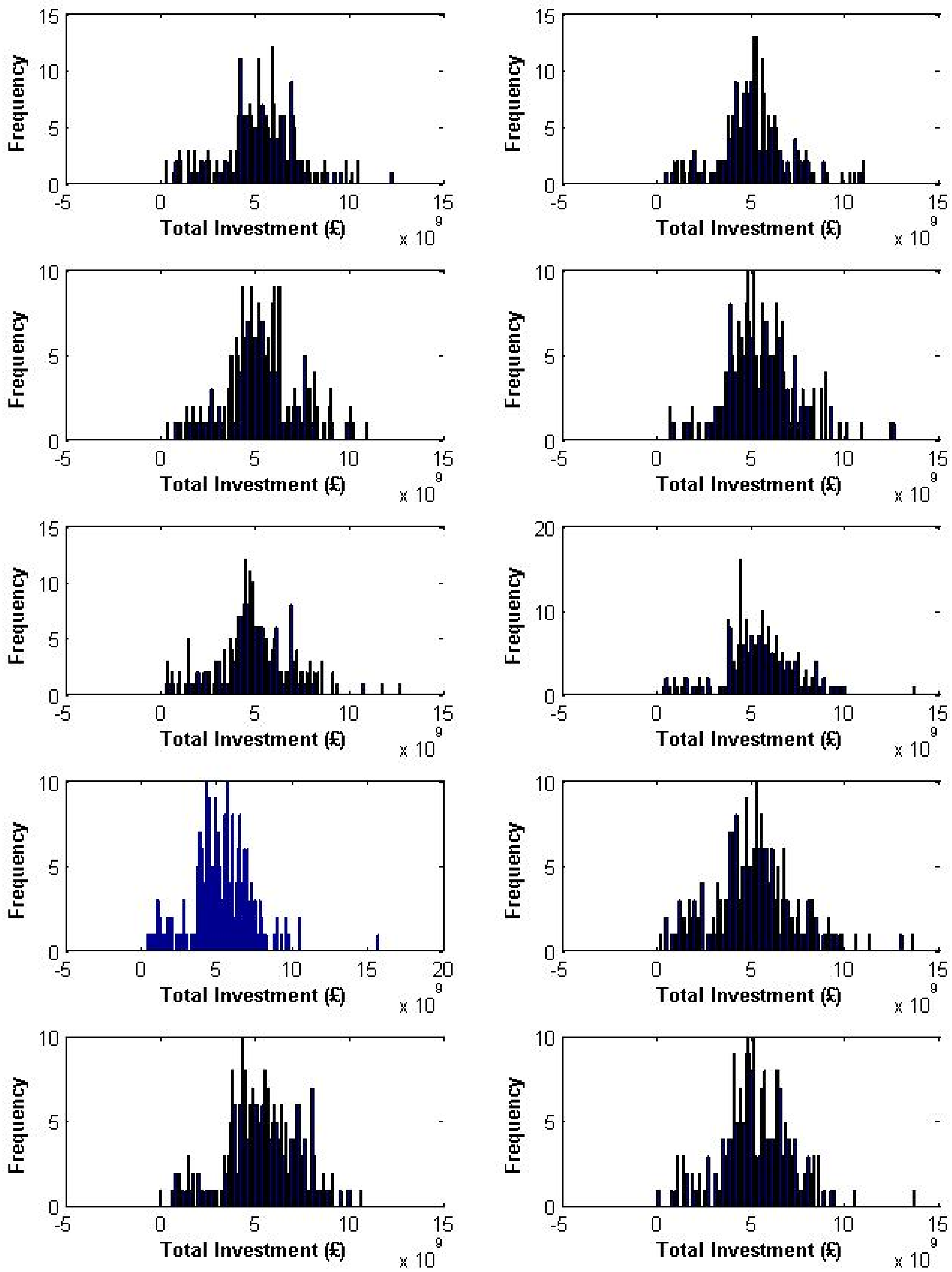

Figure C.6: Frequency Occurrence of Total Investment for all 10 runs of the Small Scale Technology Simulations.

Appendix D

Monte Carlo Simulation Model for Large Scale Technology Formative Phase

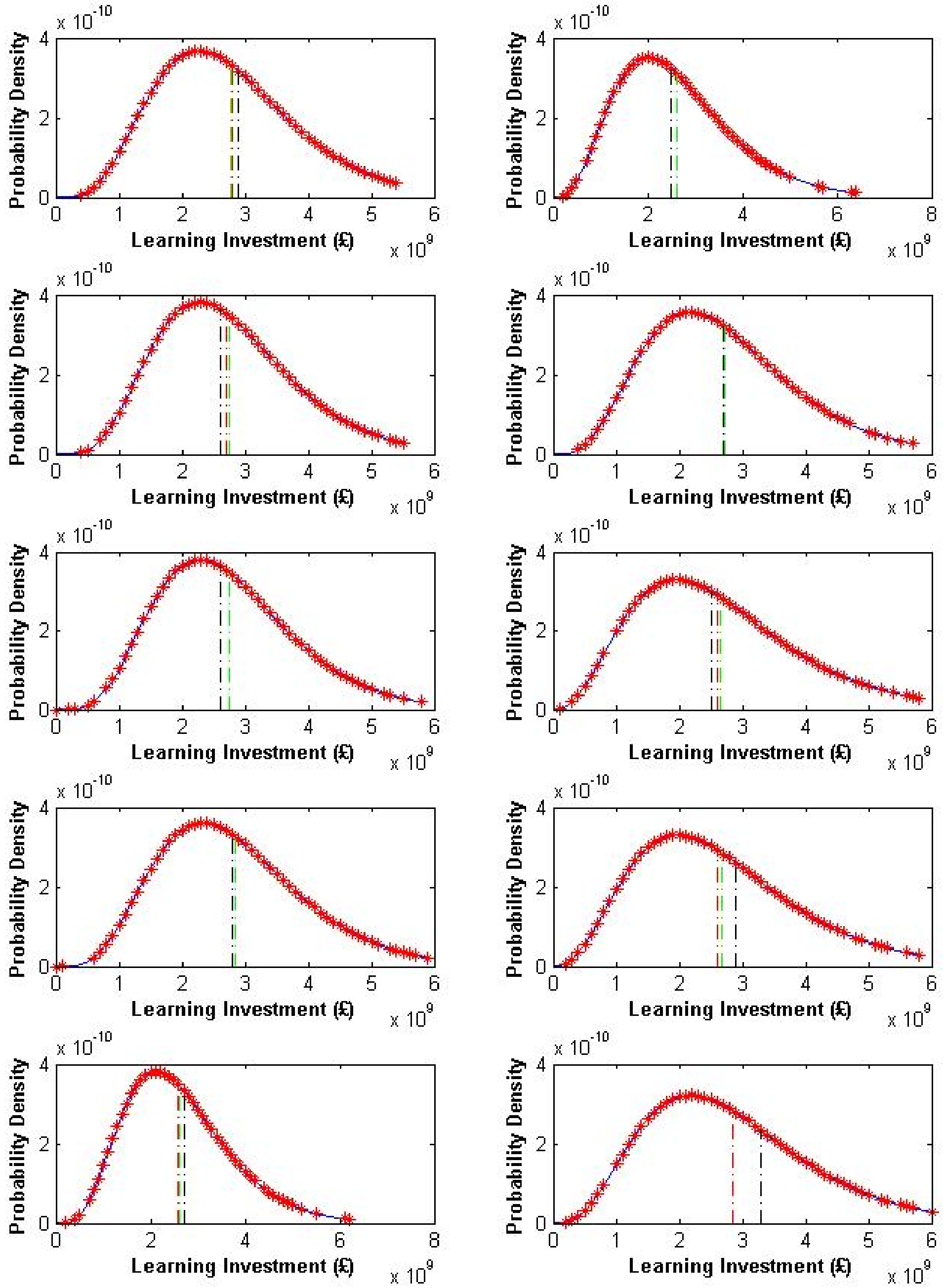

Figure D.1: PDF of Learning Investment for all 10 runs of the Large Scale Technology Simulations of the Formative Phase.

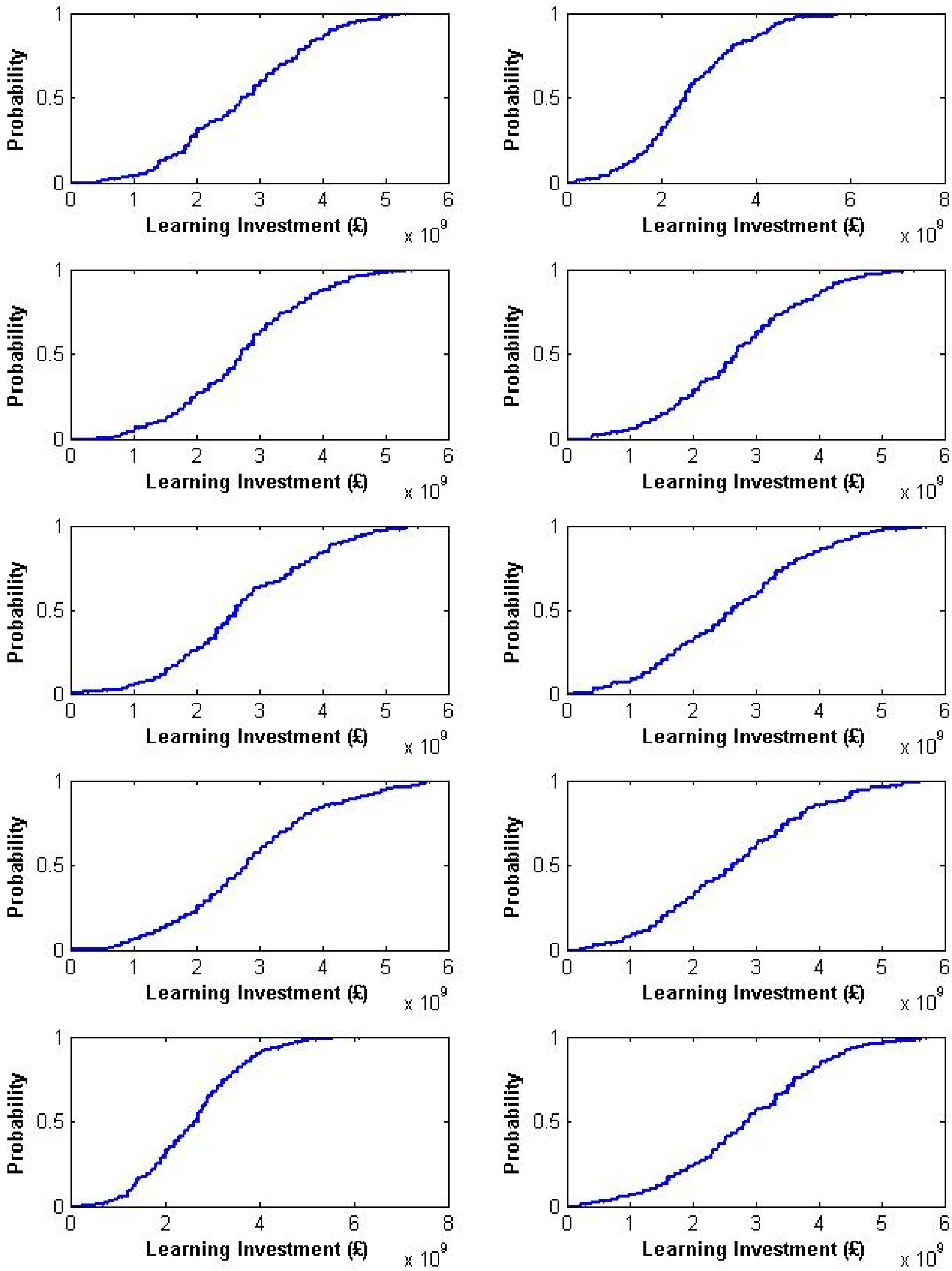

Figure D.2: CDF of Learning Investment for all 10 runs of the Large Scale Technology Simulations of the Formative Phase.

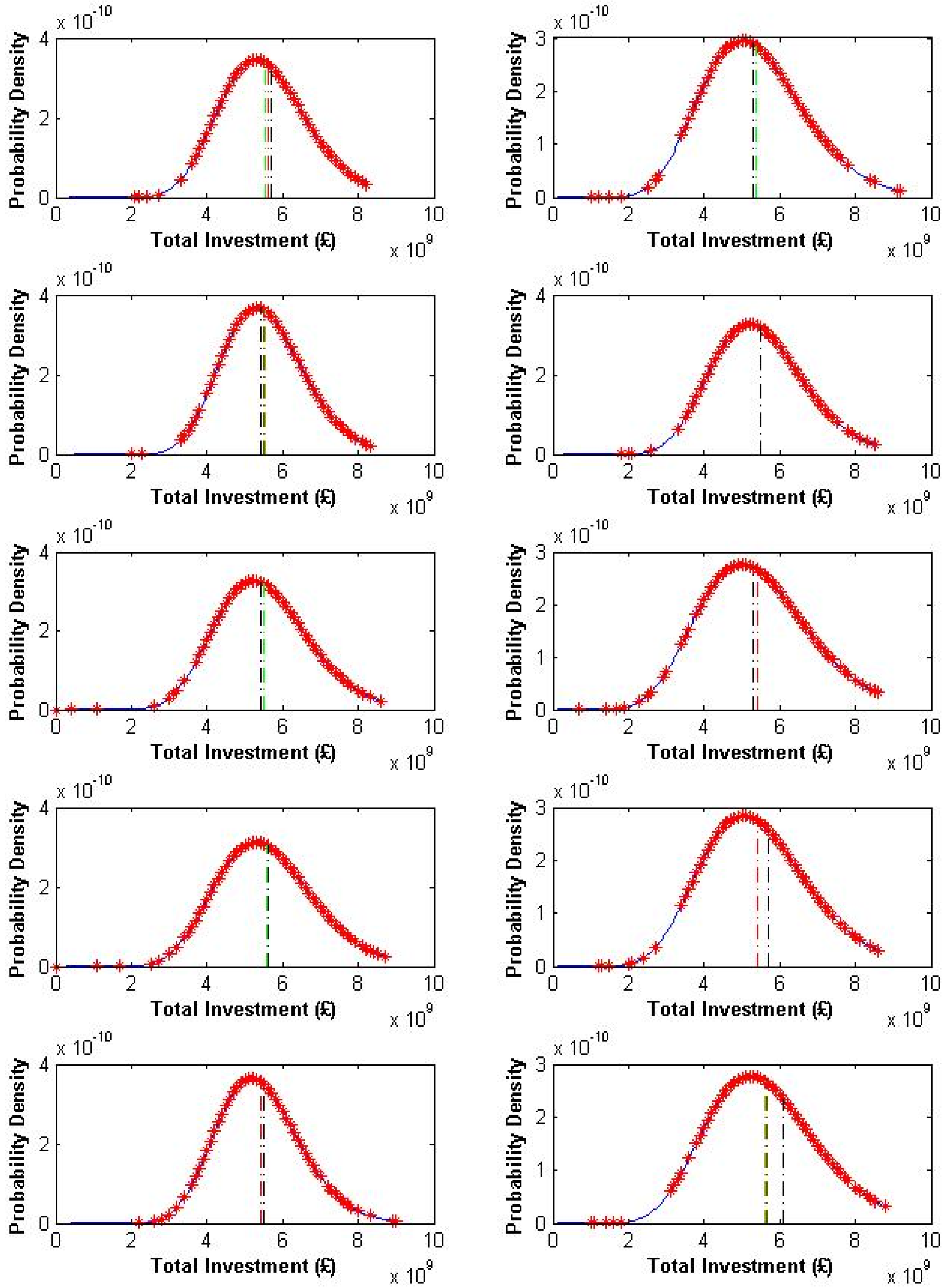

Figure D.3: PDF of Total Investment for all 10 runs of the Large Scale Technology Simulations of the Formative Phase.

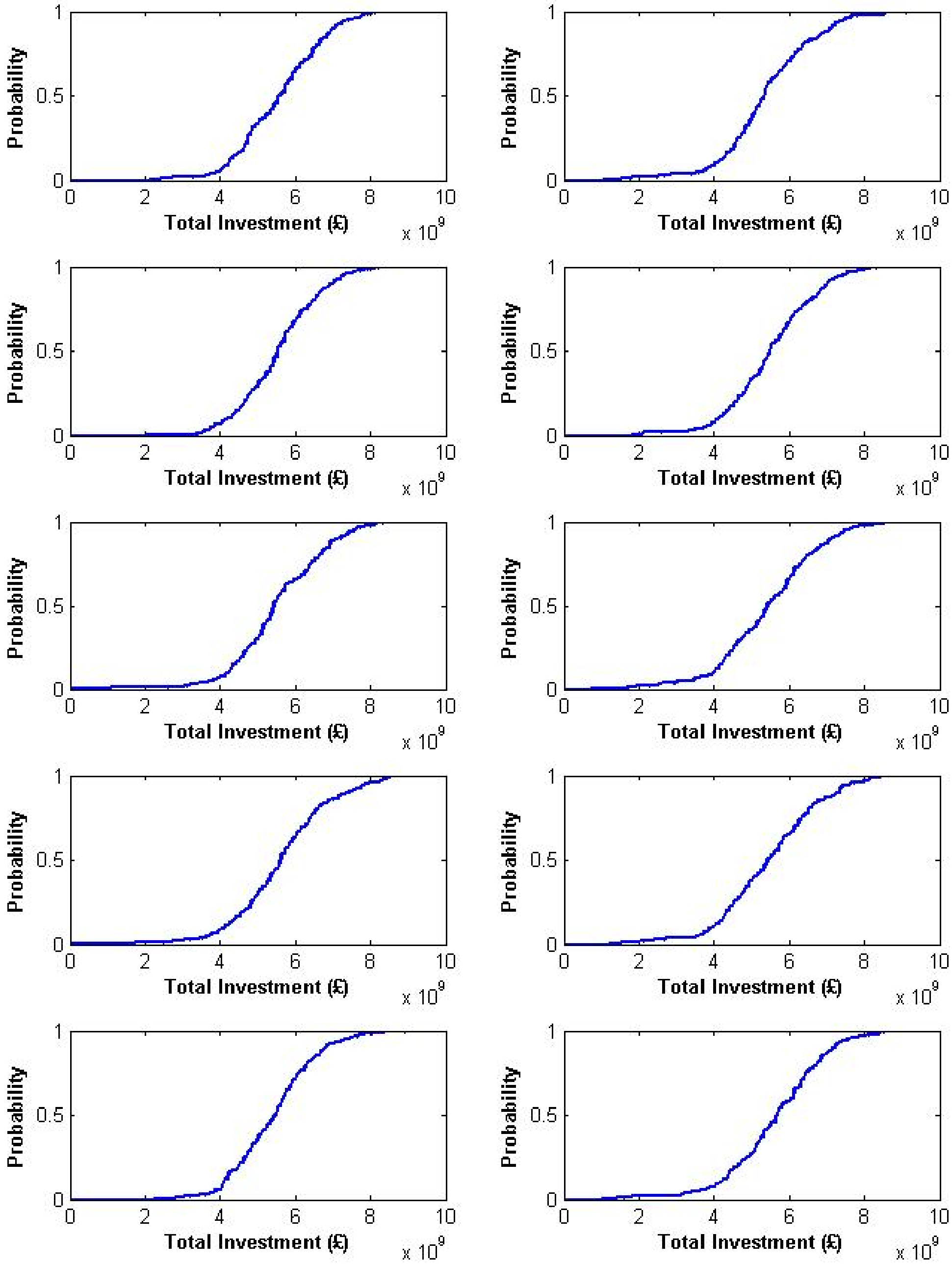

Figure D.4: CDF of Total Investment for all 10 runs of the Large Scale Technology Simulations of the Formative Phase.

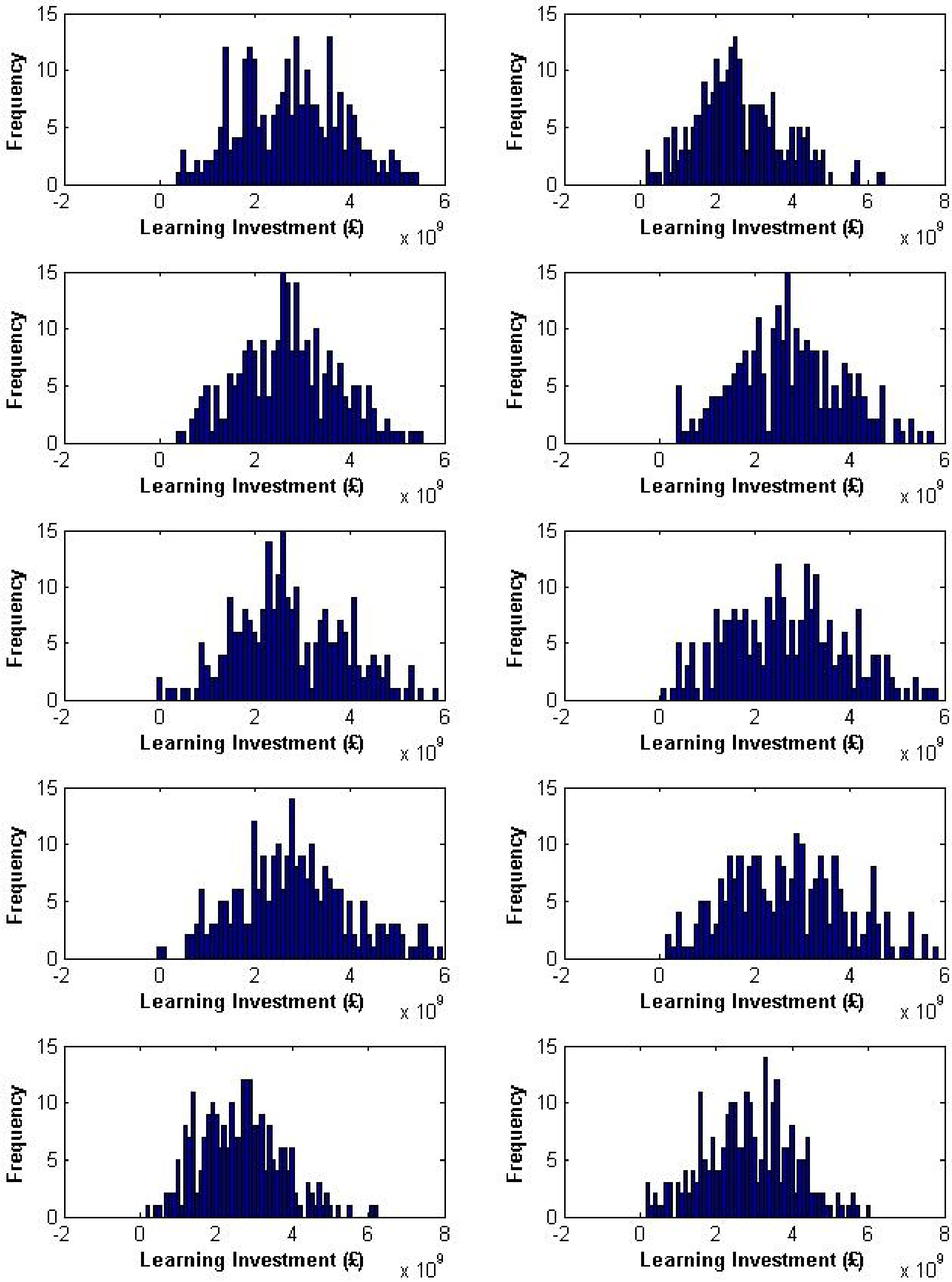

Figure D.5: Frequency Occurrence of Learning Investment for all 10 runs of the Large Scale Technology Simulations of the Formative Phase.

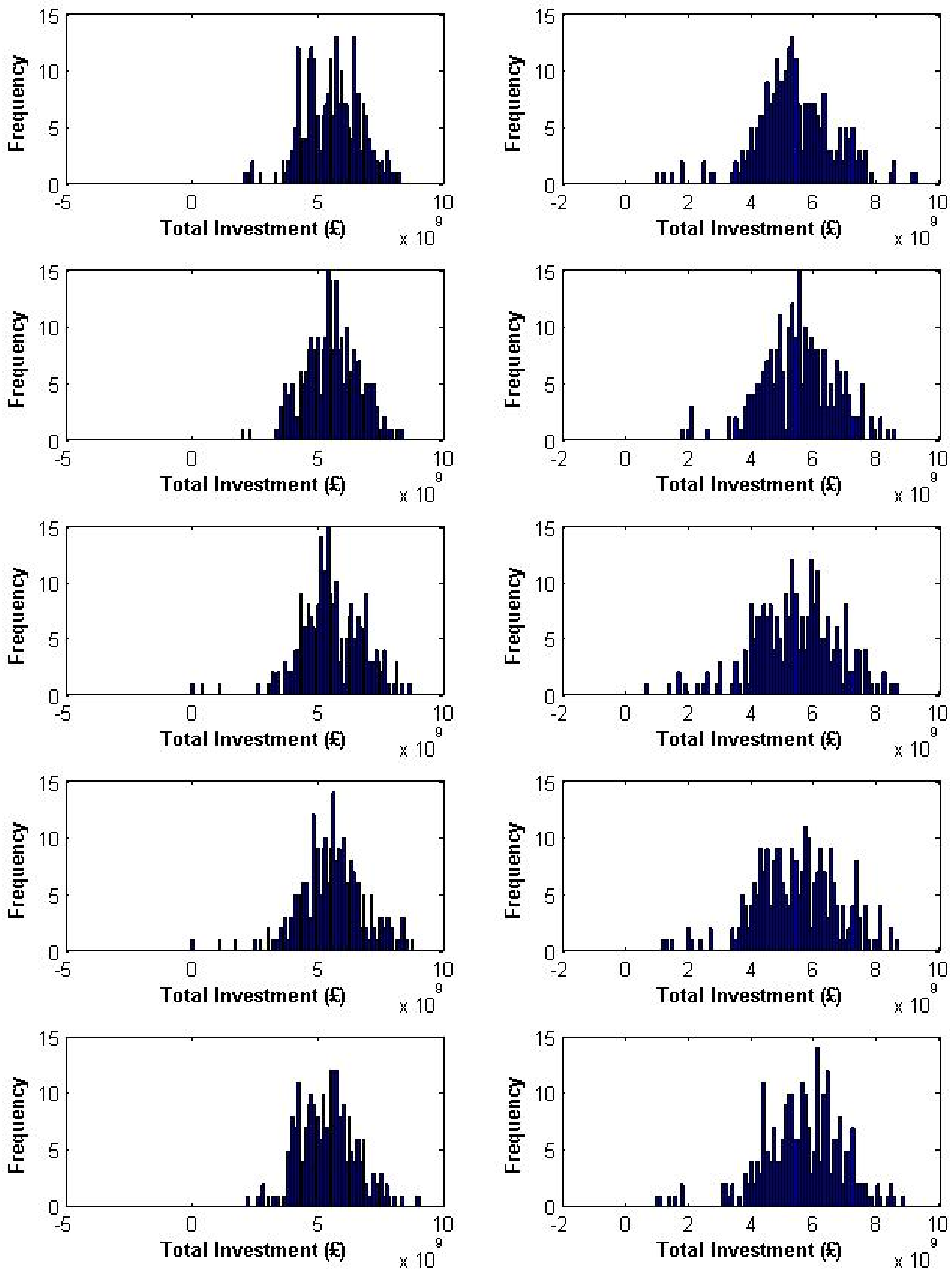

Figure D.6: Frequency Occurrence of Total Investment for all 10 runs of the Large Scale Technology Simulations of the Formative Phase.

Appendix E

Monte Carlo Simulation Model for Small Scale Technology Formative Phase

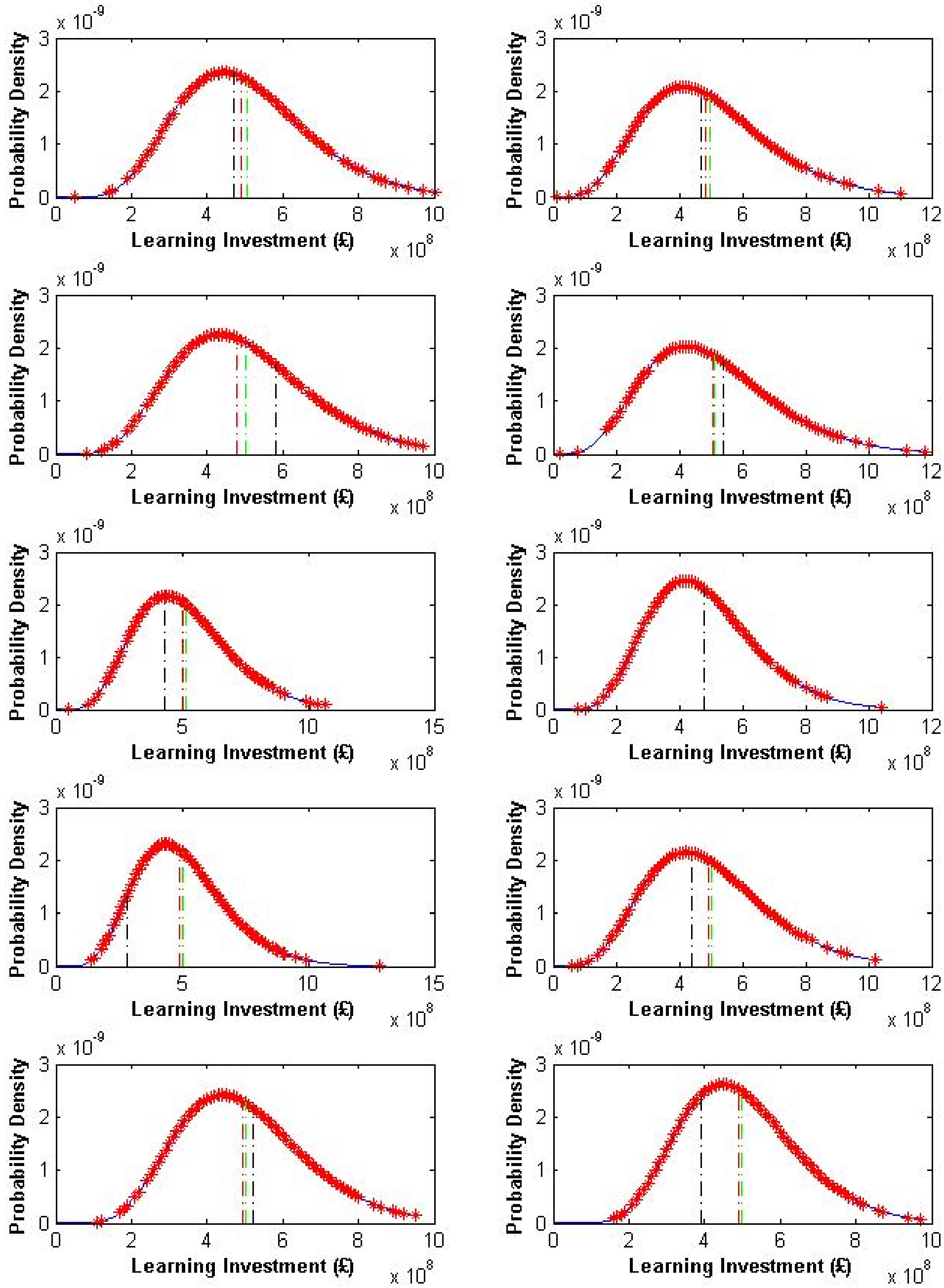

Figure E.1: PDF of Learning Investment for all 10 runs of the Small Scale Technology Simulations of the Formative Phase.

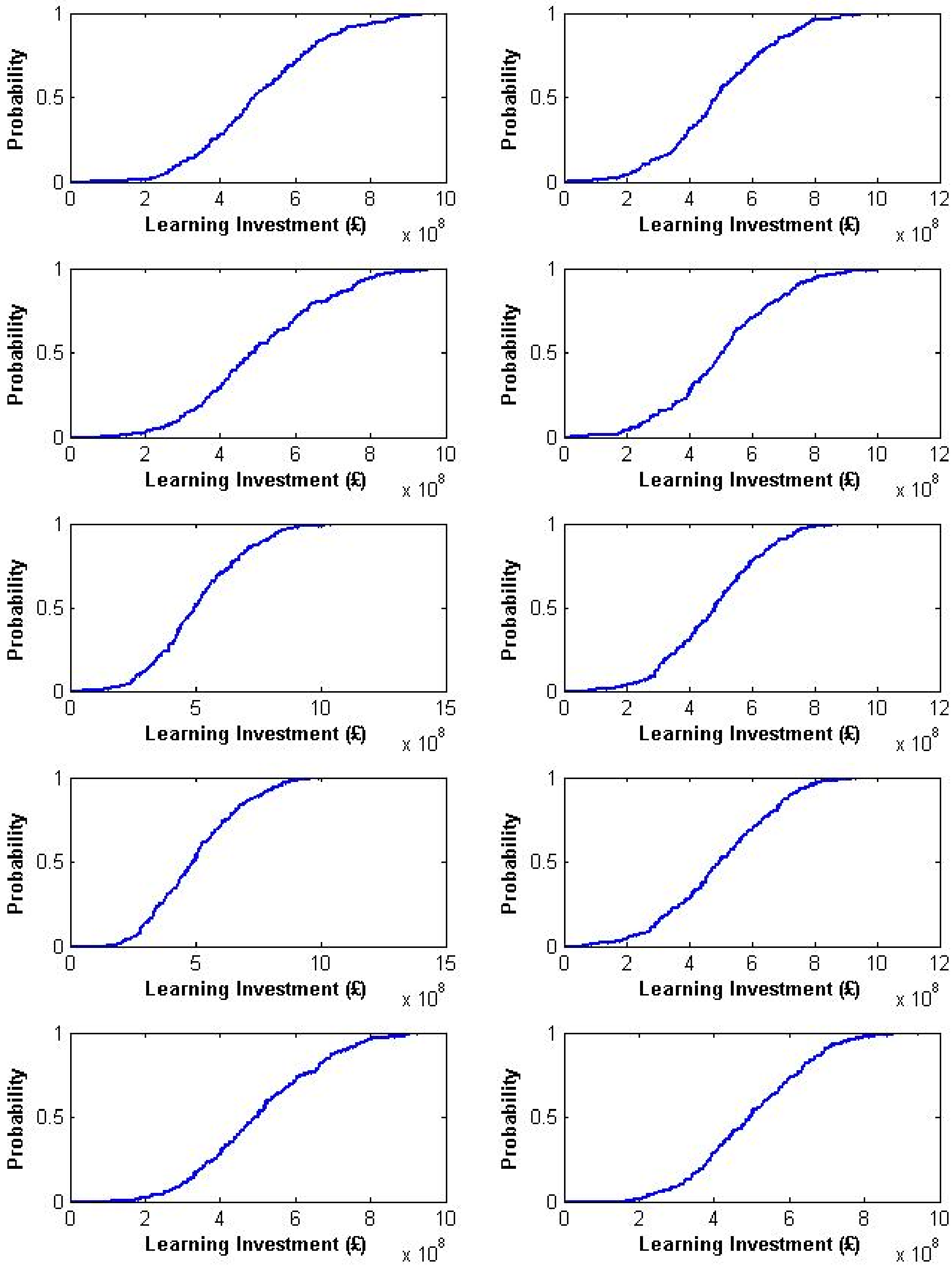

Figure E.2: CDF of Learning Investment for all 10 runs of the Small Scale Technology Simulations of the Formative Phase.

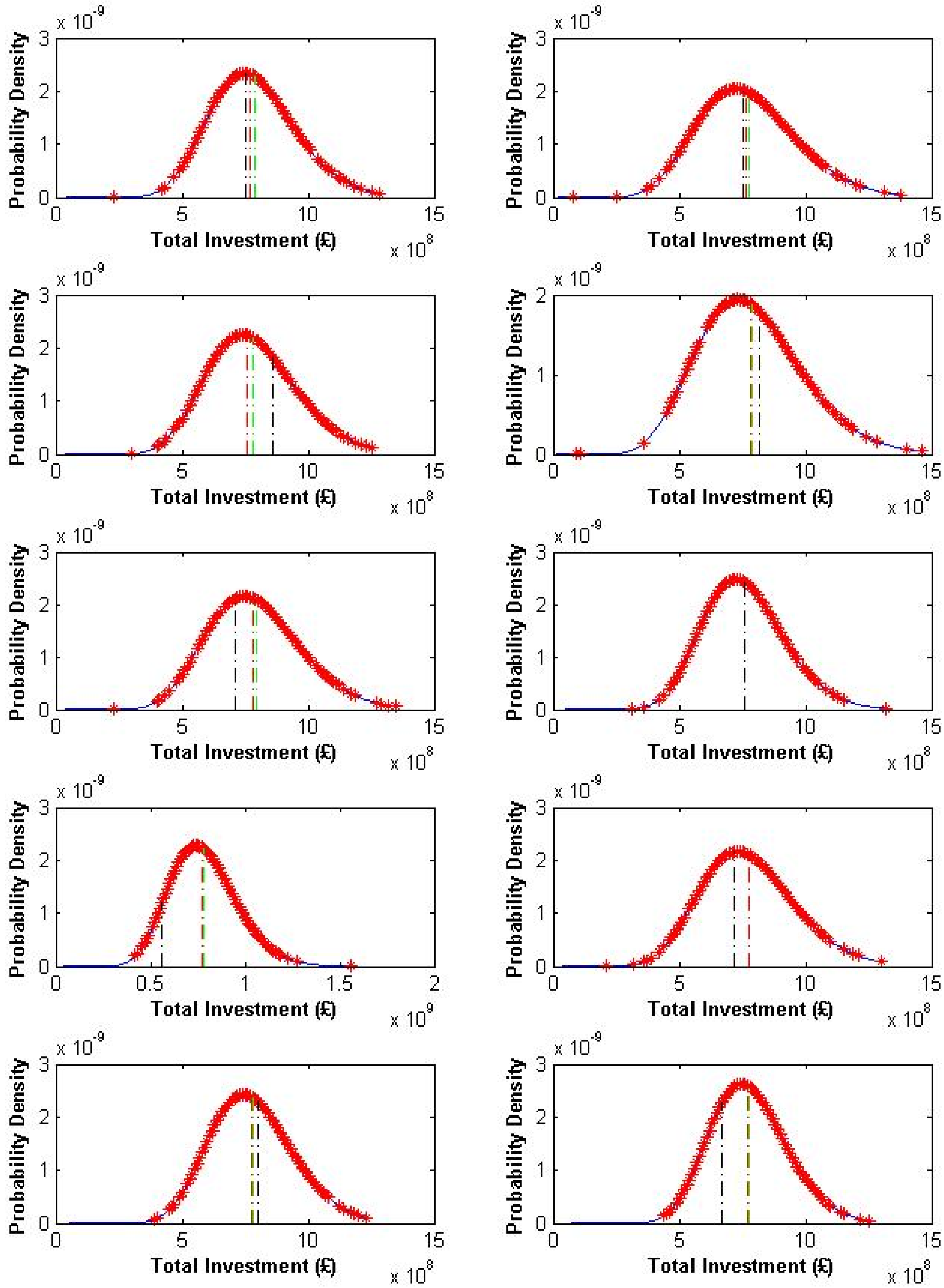

Figure E.3: PDF of Total Investment for all 10 runs of the Small Scale Technology Simulations of the Formative Phase.

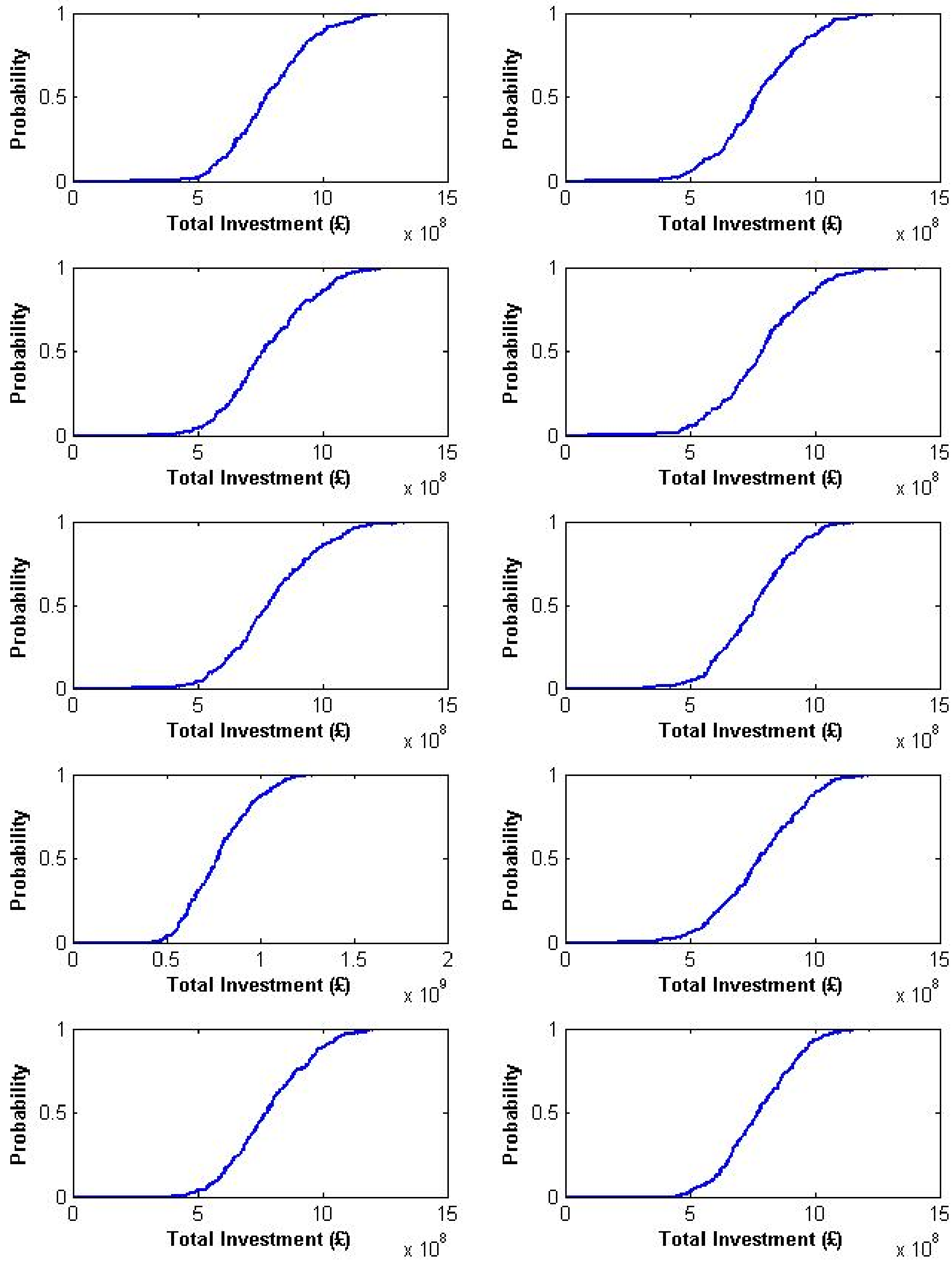

Figure E.4: CDF of Total Investment for all 10 runs of the Small Scale Technology Simulations of the Formative Phase.

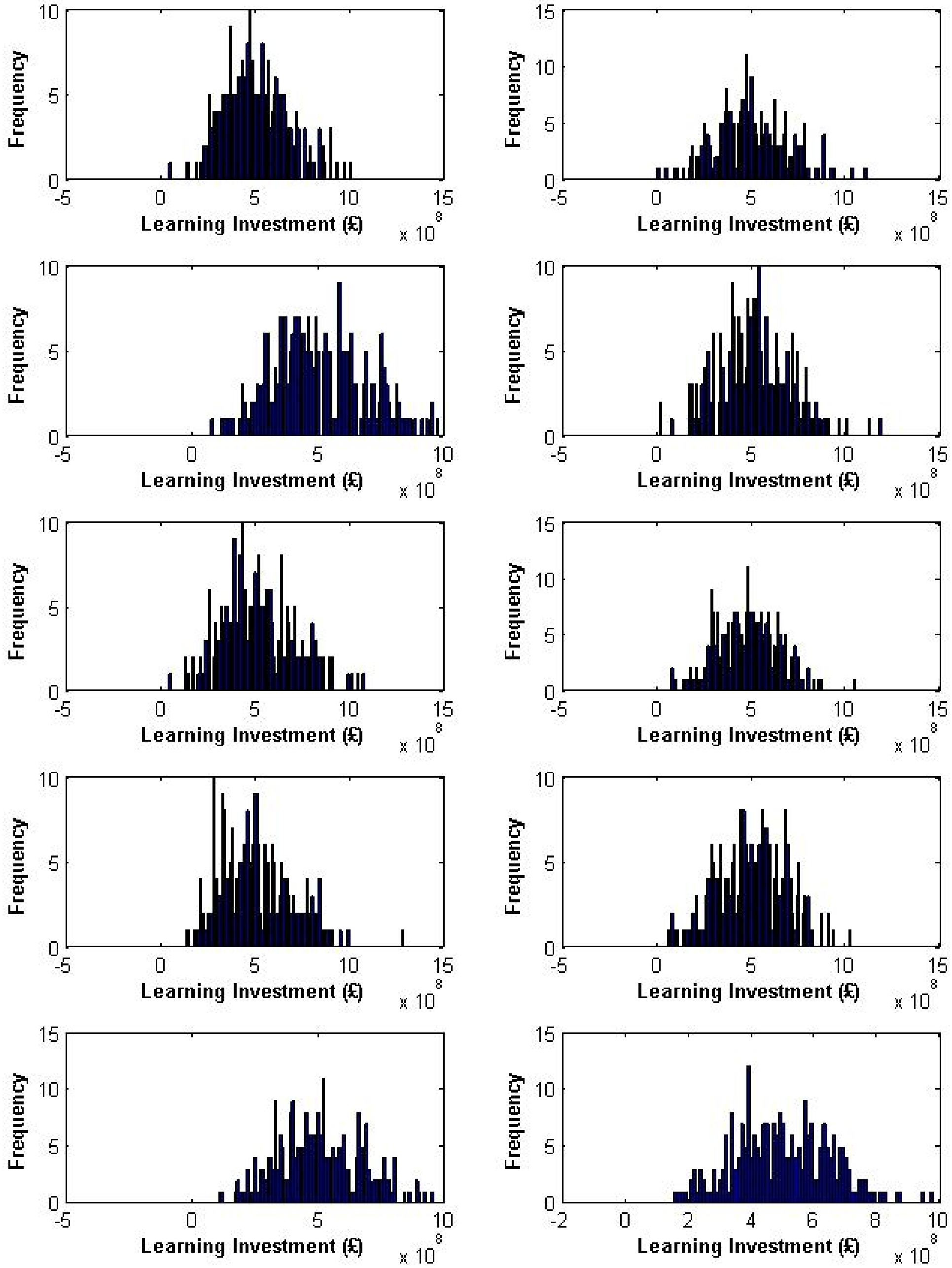

Figure E.5: Frequency Occurrence of Learning Investment for all 10 runs of the Small Scale Technology Simulations of the Formative Phase.

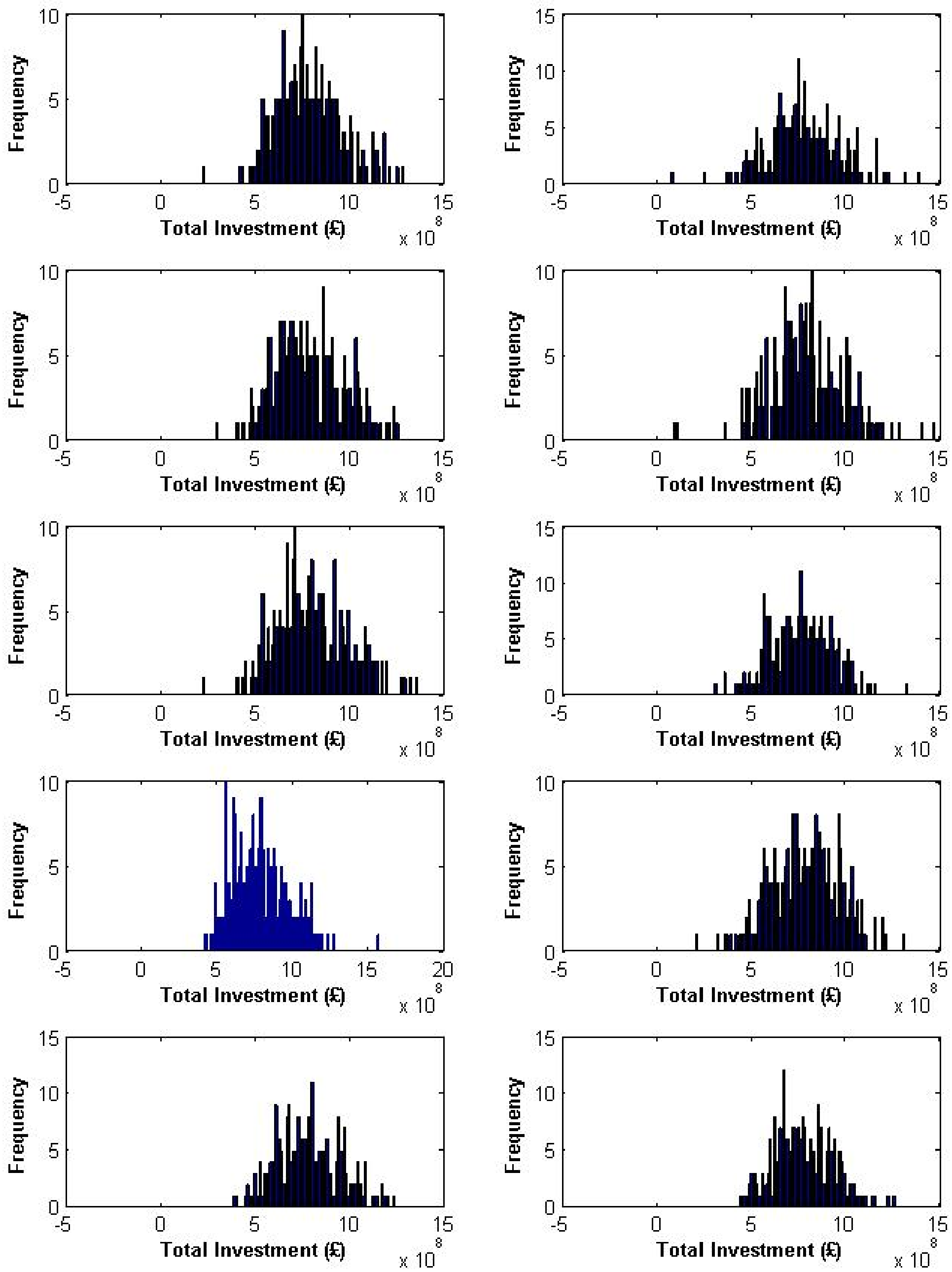

Figure E.6: Frequency Occurrence of Total Investment for all 10 runs of the Small Scale Technology Simulations of the Formative Phase.

Appendix F

Output Charts from the Learning Investment Model

F.1 Large Scale Technology

MATLAB analysis yielded the graphs shown in Figures F.1, F.2, F.3 and F.4, for each of the learning rates considered within this work. The analytical solutions are stored within a variable called "Learning_Investment", saved in the MATLAB code. The relevant file can be queried in order to find the specific learning investment values for given input parameters.

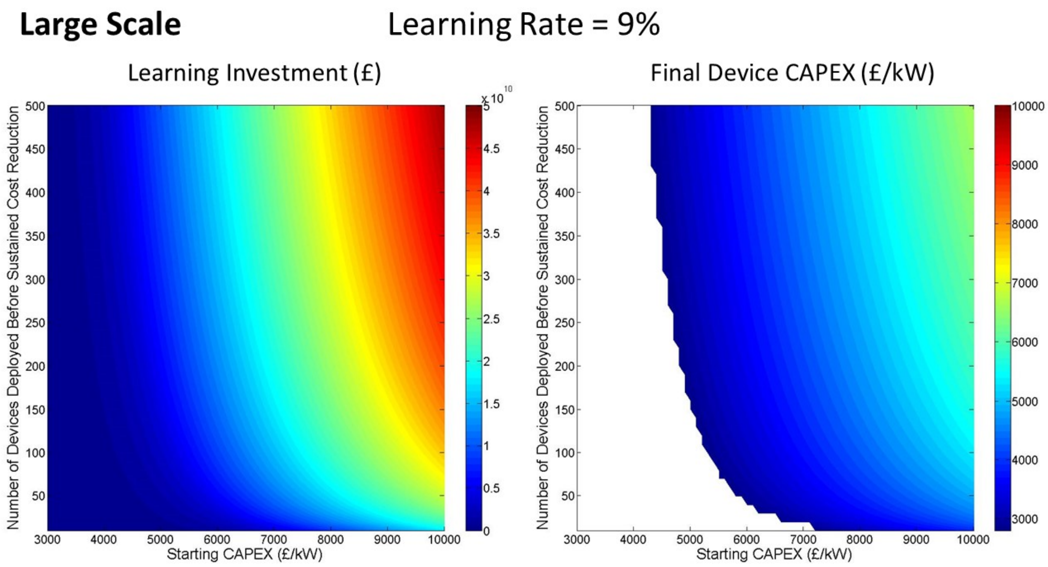

Figure F.1: Learning Investment (left) and cost of 10,000th device (right) for a 9% LR using large scale devices.

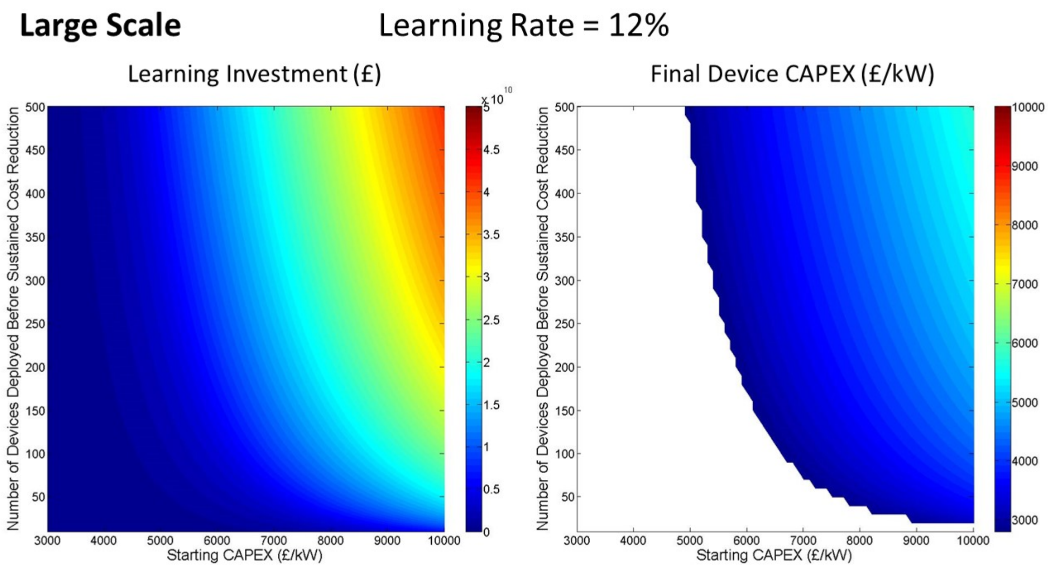

Figure F.2: Learning Investment (left) and cost of 10,000th device (right) for a 12% LR using large scale devices.

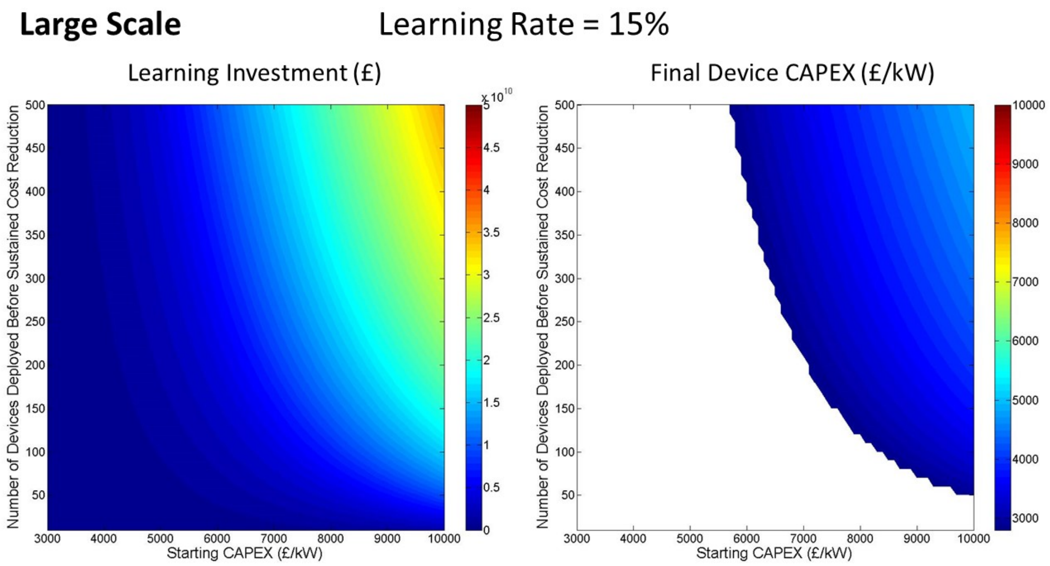

Figure F.3: Learning Investment (left) and cost of 10,000th device (right) for a 15% LR using large scale devices.

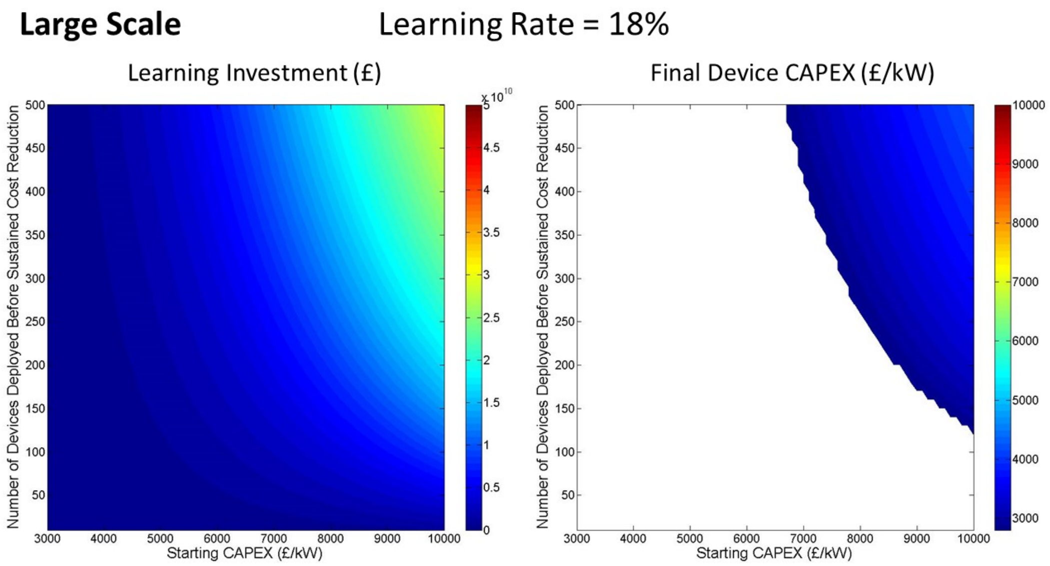

Figure F.4: Learning Investment (left) and cost of 10,000th device (right) for a 18% LR using large scale devices.

F.2 Small Scale Technology

MATLAB analysis of all parameter perturbations using small scale technology resulted in the graphs shown in Figures F.5, F.6, F.7 and F.8, for each of the learning rates considered within this work. It should be noted that the colour bar scale in the small scale technologies is an order of magnitude lower than for the large scale technologies. In the small scale technology learning investment scenarios, the maximum learning investment was in the order of £10 billion; for the large scale technology, the maximum was £100 billion.

The analytical solutions to each scenario are again stored within a variable called "Learning_Investment", saved in the MATLAB code. The relevant file can be queried in order to find the specific learning investment values for given input parameters.

While it is of course understandable that a smaller capacity wave or tidal energy converter would coincide with a lower unit capital cost (not cost per kW), the trade off in terms of reduced net power output per unit has resulted in a lower attractiveness for smaller scale prototypes from the vast majority of technology and project developers, particularly within the UK. Utilising smaller scale technology will only be capable of achieving relatively modest installed capacities when compared to an equivalent number of unit deployments of MW-scale technology.

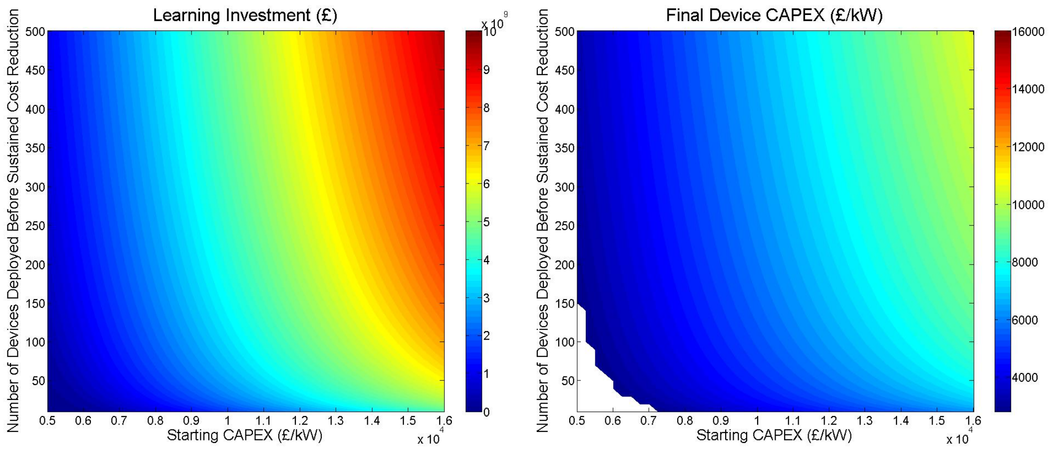

Figure F.5: Learning Investment (left) and cost of 10,000th device (right) for a 9% LR using small scale devices.

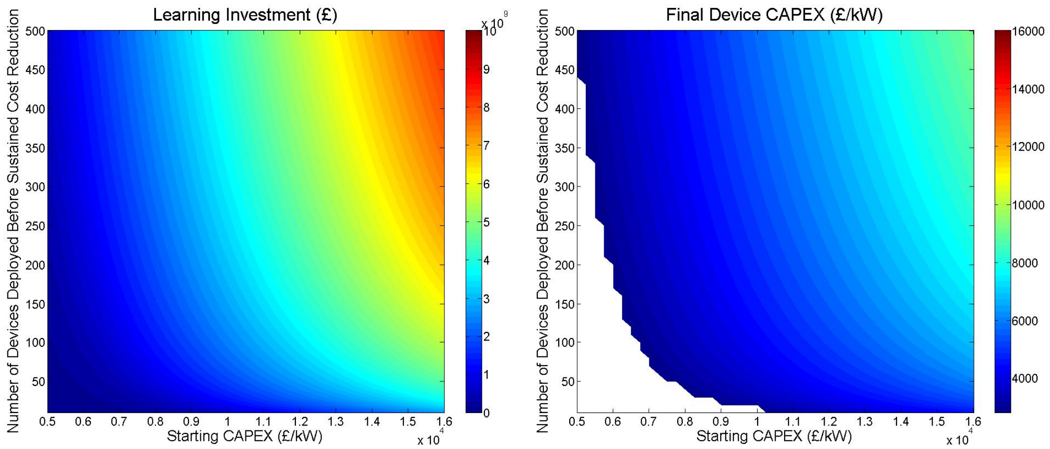

Figure F.6: Learning Investment (left) and cost of 10,000th device (right) for a 12% LR using small scale devices.

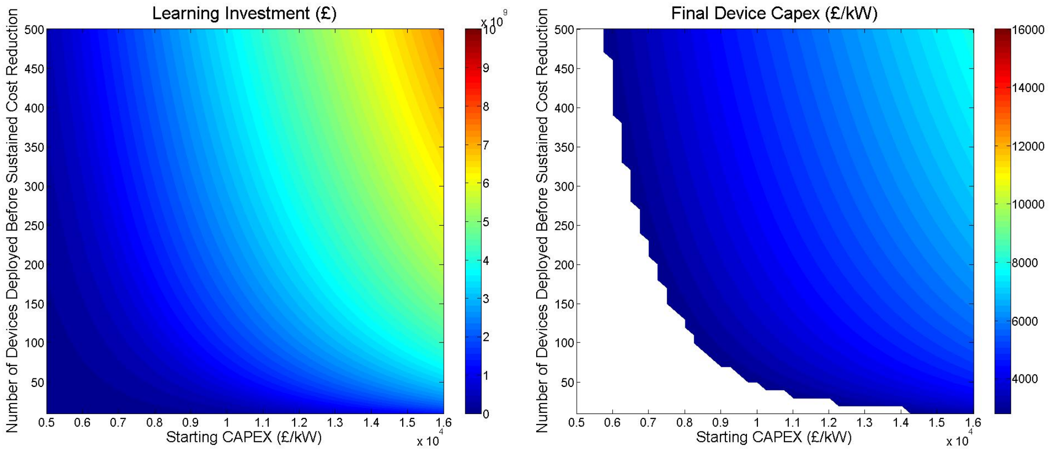

Figure F.7: Learning Investment (left) and cost of 10,000th device (right) for a 15% LR using small scale devices.

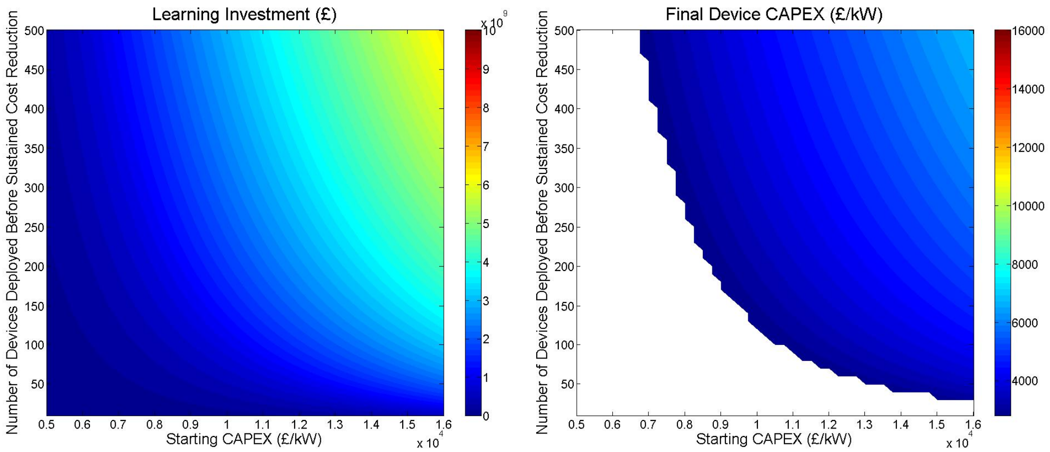

Figure F.8: Learning Investment (left) and cost of 10,000th device (right) for a 18% LR using small scale devices.